
Cost-Benefit Analysis of Treating Saline Groundwater

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GLOSSARY

AENV	Alberta Environment
BGWP	Base of Groundwater Protection (the depth at which the total dissolved solids concentration exceeds 4,000 milligrams per litre)
CBM	Coalbed methane
DEQ	Department of Environmental Quality (Wyoming)
EDR	Electrodialysis (Reversal)
EUB	Energy and Utilities Board (Alberta)
mg/L	milligrams per litre
NPDES	National Pollutant Discharge Elimination System
pers. comm.	personal communication
RO	Reverse Osmosis
TDS	Total Dissolved Solids
UIC	Underground Injection Control
USDW	underground source of drinking water
USEPA	United States Environmental Protection Agency
ZLD	Zero Liquid Discharge

SUMMARY

Groundwater in Alberta with a total dissolved solids concentration of less than 4,000 milligrams per liter is protected under the Water Act as non saline and potentially potable water. Recent initiatives have identified water currently considered saline as a potential resource in Alberta. Currently this water is being used for oilfield injection, however with treatment this water could be used for drinking or agricultural purposes for salt tolerant crops, as is undertaken in many other parts of the world today (such as southern United States, Israel and Jordan).

A review of groundwater regulations in other provinces, a number of states in the United States and internationally indicates a range of approaches to groundwater protection and management. British Columbia has applied an aquifer classification program based on the degree of development and aquifer vulnerability that is aimed at providing protection to groundwater resources. Other provinces regulate groundwater use, but often do not distinguish between saline and non saline groundwater. The United States Environmental Protection Agency proposed a classification system that recognizes groundwater with total dissolved solids less than 10,000 milligrams per litre as a potential source of drinking water. Many states have developed their own classification system, modified from the United States Environmental Protection Agency, primarily for protection of groundwater resources.

A number of established desalination technologies that are in worldwide use have been identified. However, only a small number of these are considered to be potentially cost-effective for desalination of brackish groundwater in Alberta. The applicable desalination technologies are essentially limited to reverse osmosis and electrodialysis, based on costs, suitability for the quality of the potential source water (brackish), and the established use of these same methods in other areas such as Saskatchewan and Texas. Desalination technologies are most cost-effective for potable water supplies, compared to agricultural use.

Desalination produces concentrate. There are several concentrate management methods in use as well, however, they all have their limitations in terms of costs, regulatory barriers, and local challenges. Deep well injection is already being practiced in the oil and gas sector, and is viable in some areas in the Province. Evaporation ponds are costly, but for small facilities they may be feasible. Zero liquid discharge is also costly, but may be the most cost-effective in terms of land costs where injection wells are not a viable option.

Costs of desalinated brackish water, based on our review of practices in other jurisdictions, would likely be 3 to 5 times higher than the current costs of usable water in Alberta. Costs are generally lower for product water from larger facilities due to economy of scale principles. They are greater, however, for product derived from poorer-quality (more saline) feed water.

1.0 INTRODUCTION

Groundwater in Alberta with total dissolved solids (TDSⁱⁱ) of less than 4,000 milligrams per litre (mg/L) is protected under the Water Act as non saline and potentially potable water. The final report prepared by the Coal Bed Methane (CBM)/Natural Gas in Coal Multi-Stakeholder Advisory Committee (Multi-stakeholder Advisory Committee 2006) suggested that water with TDS greater than 4,000 mg/L should be investigated for potential treatment and use. The potential value of this resource was recognized, particularly as basins in Alberta become fully allocated, such as the South Saskatchewan basin. Recommendations included in the Multi-stakeholder Advisory Committee report (2006) advised that:

- a use assessment for marginally saline groundwater, with criteria and guidelines, should be included as part of the approval process; and
- the development or application of technologies to take advantage of marginally saline produced water should be promoted.

In other parts of the world marginally saline or even saline water is treated and used for a variety of uses, due to the scarcity of fresh water resources. The United States Environmental Protection Agency (USEPA), for example, included brackish waters, i.e., TDS 3,000 to 10,000 mg/L, within protected groundwater sources (Pretula, 1984).

This report provides an overview of the regulations regarding groundwater use and protection in other jurisdictions and available technologies for the treatment of marginally saline water. This information is reviewed to evaluate the potential cost benefits of increasing the TDS of useable groundwater in Alberta. This report includes the following:

- A summary of how the use and protection of groundwater is undertaken in other jurisdictions.
- An overview of available technologies to treat groundwater with TDS between 4,000 mg/L and 10,000 mg/L and the methods for concentrate management
- Establishment of the upper salinity limit for the economic treatment of groundwater in consideration of various uses and users applicable within Alberta.
- Recommendations regarding the implementation of the use of groundwater with TDS between 4,000 and 10,000 mg/L.

The benefits and drawbacks of the various desalination technologies including a cost comparison and feasibility analysis for Alberta were used in order to identify the upper salinity limit for the economic treatment of groundwater in Alberta. Feasibility summary also considers potential increases in costs for water compared to the current cost in Alberta.

ⁱⁱ Total Dissolved Solids (TDS) concentrations are comprised of dissolved inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulphates) and small amounts of organic matter (WHO 2004).

2.0 STUDY APPROACH

Information for this report came from published literature (reports, papers etc.), unpublished publicly available information (internet, news articles, etc.) and personal interviews.

Interviews were conducted to better understand the benefits and drawbacks of some of the technologies as well as the practical aspects of applying some of the regulations researched.

Interviews were conducted with the representatives from the following organizations and companies:

- Province of Saskatchewan, Saskatchewan Water Board;
- Province of British Columbia, Ministry of Environment;
- Province of Manitoba, Manitoba Water Services Board and Manitoba Water Control;
- State of Texas, Texas Water Development Board;
- State of Wyoming, Department of Environmental Quality;
- Zenon, Ontario (vendor of desalination products); and
- Mickley and Associates, Texas (experts in concentrate management).

The minutes from the interviews are included in Appendix A.

3.0 BACKGROUND

3.1 Groundwater Use in Alberta

Currently only 2.5 % of consumptive water use in Alberta is from groundwater sources, the remaining 97.5 % is from surface water. In Alberta, excluding domestic use, most groundwater licences have been issued for agricultural purposes (29%). The other main uses of groundwater are for oil recovery (18%), industrial (including oil, gas petroleum) (19%) and municipal (19%) (Alberta Environment (AENV) 2005). The remainder of the uses include commercial uses, habitat enhancement, fish management, irrigation etc. There are approximately 500,000 domestic wells in Alberta with about 7,000 added each year (AENV, 2005). The use of non-saline groundwater in enhanced oil recovery has declined since the mid 1970's. The use of water for thermal oil recovery could increase due to rapid expansion of the oils sands and heavy oil sector. The concern with using non-saline groundwater for injection compared to other uses is that it removes this water as a practical potential groundwater for future use. It is believed that currently the use of marginally saline groundwater is limited to oil and gas sector.

3.2 Groundwater Quality by Use

The quality of water required by various use sectors is dependent on the purpose for which the water is being used. The aesthetic objective for drinking water is a TDS of 500 mg/L (Health Canada, 2006). There is no international health-based guideline for TDS because there is no reliable data regarding the health effects of ingestion of TDS on humans (World Health Organization, 2004). In 1958 World Health Organization (WHO) proposed a value of 1500 mg/L as the maximum allowable limit, however this was strictly based on taste. The guideline value was modified to 1000 mg/L in 1984 and 1200 mg/L in 1993. In some water short countries such as in the Middle East the guideline is higher the current WHO guideline, for example the Oman government classifies potable groundwater as having a TDS concentration less than 1,500 mg/L (Parsons International and Company, 2005).

With respect to agriculture, water quality guidelines have been developed by the Canadian Council of Ministers for the Environment for livestock and crop tolerances, which have been adopted for use in Alberta (AENV, 1999). The TDS guidelines for crop tolerances are provided in Table 1 and range between 500 and 3500 mg/L (Canadian Council of Ministers for the Environment, 1999). The Canadian Council of Ministers for the Environment water quality guidelines (1999) indicates TDS should be less than 3000 mg/L for livestock watering. Information from the Prairie Farm Rehabilitation Association (adapted from the USEPA) is provided in Table 2 and shows a detailed breakdown of TDS concentrations and livestock tolerances.

**Table 1 Tolerance of Selected Crops to TDS Concentration in Irrigation Water
(Canadian Council of Ministers for the Environment, 1999)**

Total Soluble Salts Content of Water (mg/L)	Tolerant Fruits and Berries in Order of Tolerance	Tolerant Vegetables in Order of Tolerance	Tolerant Field Crops in Order of Tolerance	Tolerant Forages in Order of Tolerance
<500	Strawberry, raspberry	bean, carrot	bean	
<800	Boysenberry, currant, blackberry, gooseberry, plum, grape, apricot, peach, pear, cherry, apple	onion, parsnip, radish, pea, pumpkin, lettuce, pepper, muskmelon, sweet potato, sweet corn, potato, celery, cabbage, kohlrabi, cauliflower	cowpea, broadbeans, flax, sunflower, corn	
<1,500	Spinach, cantaloupe, cucumber, tomato, squash, brussel sprout, broccoli, turnip, wheatgrass			brome, alfalfa, big trefoil, beardless, wildrye, vetch, timothy, crested
<2,500		Beet, zucchini	rape, sorghum	oat hay, wheat hay, brome mountain, tall fescue, sweet clover, reed, canary grass, birdsfoot, trefoil, perennial, ryegrass
<3,500		Asparagus	soybean, safflower, oats, rye, wheat, sugar beet, barley	barley hay, tall wheatgrass

Table 2 Guide for the Use of Saline Water for Livestock Watering (Prairie Farm Rehabilitation Association)

Total Soluble Salts Content of Water (mg/L)	Suitability for Livestock
<1,000	Relatively low level of salinity; excellent for all classes of livestock
1,000 – 3,000	Satisfactory for all classes of livestock and poultry, but some loss in productivity should be anticipated; may cause temporary and mild diarrhea in livestock not accustomed to them or watery droppings in poultry
3,000 – 5,000	Satisfactory for livestock, but may cause temporary diarrhoea or be refused at first by animals not accustomed to them; poor waters for poultry, often causing watery faeces, increased mortality and decreased growth, especially in turkey
5,000-7,000	Can be used with reasonable safety for beef, cattle, sheep, swine and horses; avoid use for pregnant or lactating animals and dairy cattle; not acceptable for poultry
7,000 – 10,000	Unfit for poultry and probably for swine; considerable risk in using pregnant or lactating cows, horses or sheep or for the young of these species, in general, use should be avoided, although older ruminants, horses, poultry and swine may subsist on them under certain conditions
>10,000	Risks with these highly saline water are so great that they cannot be recommended for use under any conditions

The use of saline or brackish water for irrigation has been successful in many parts of the world (Parsons International and Company, 2005). In order for agriculture to use brackish water in an economic and environmentally sustainable way, it must be strategically planned. There are methods that can be used to control the leaching of salts and preventing deterioration of fresh water. Examples of suitable management practices are cyclic application, crop selection, deep ploughing, minimum leaching requirements, placing seed on sloping or modified seed-beds etc. A study in 2000 by the Institute of Research found that some crops such as tomatoes irrigated with brackish water produced better higher quality crops compared to using lower salinity water (Parsons International, 2005). In Pakistan the most economical crop is Kallar grass which has actually shown improvement in soil properties when irrigated with brackish water compared to being irrigated with fresh water. All over the world saline water has been used on its own or mixed with fresh water, for irrigation; countries such as Israel, Egypt, Tunisia, Jordan, Pakistan, India and the United States have been doing so for years.

3.3 Cost of Water in Alberta

Consumers pay for the cost of water treatment and delivery in Alberta. Consumers do not pay for using the water or environmental costs for withdrawing the water. This applies to residential users, agriculture and industry (AENV, 2002a). Determining the full cost of providing water is one of the initiatives of the Alberta Water for Life Strategy (AENV, 2002a).

Environment Canada has indicated that the price of water is expected to increase in Canada in the future (Environment Canada, 2006). A study by the Pembina Institute used data from Statistics Canada to indicate that cost of treating and supplying water has increased steadily in Alberta on a per capita and total basis from 1970 to 1998, reaching \$130 per person in 1998.

There is ongoing debate about charging for water in Alberta (e.g., CBC News, 2006). Jim Oosterbaan of Epcor, the Edmonton utility company, has stated that "The real cost of water in Alberta should be about \$1.50 per cubic meter" (Enviroline, 2007). The potential for future increases in the cost of withdrawing and treating water does highlight several points; (1) that the total costs of treated brackish water could increase from those identified in this study depending on whether pricing is also applied to brackish water and (2) any gap between current and treated brackish water costs could decrease due to future costs increases. As the future cost of water in Alberta is unknown and no information regarding the tolerance of water costs by use sector was available, costs of treated water are compared to current costs by use sector. Current costs are reviewed in the following discussion.

Typical capital costs for agricultural water supplies range from \$400 to \$7,000ⁱⁱⁱ and could range up to \$16,000 for a groundwater well (Alberta Agriculture, Food and Rural Development, 2003; AENV, 2002b). Annual maintenance costs are typically between \$60 and \$350, although water hauling is more expensive and ranges up to \$2,500 per year. Costs for maintenance are typically less than \$0.10 per m³ in Alberta, whereas water hauling is roughly \$6.26 per m³ in Alberta and Saskatchewan (Agriculture and Agri-Food Canada, 2005). Rural water societies exist where multiple landowners invest in a water system to supply all members. The Roselawn Water Development Society, for example, formed in 1986 with an initial investment of \$8,190 and ongoing cost of \$0.0008 per m³ (Kenzie).

Water licenses under the Water Act are charged based on the amount of the withdrawal, for example an annual withdrawal less than 62,500 m³ has no charge, whereas a license of between 121,501 to 125,000 m³ is \$150. These fees cover the administrative costs related to license issue.

Irrigation fees are paid based on the area irrigated, not based on the quantity of water used. The fees range from \$16.25 (plus a pressure surcharge) per assessed acre per year to \$7.50 (plus a pipeline surcharge) depending on what irrigation district you are in (Alberta Agriculture, Food and Rural Development, 2005). The top three irrigation districts at the upper end of this range are the Bow River Irrigation District, the Lethbridge Northern Irrigation District and the Western Irrigation District.

ⁱⁱⁱ All amounts are 2006 Canadian currency

4.0 REGULATIONS

Regulations within a number of jurisdictions, primarily Canadian provinces and selected American states, are summarized in the following discussion. Regulations reviewed are those that pertain to protection and regulation of groundwater, particularly with respect to TDS concentration and any aquifer classification system that has been adopted. As concentrate disposal is a substantial consideration with desalination, regulations concerning this activity are also reviewed. This includes deep well injection regulations.

4.1 Alberta

4.1.1 *Groundwater Regulations*

The protection and management of groundwater in Alberta mainly falls under the *Water Act* (Province of Alberta, 1996). The *Water Act* came into force in 1999, replacing the *Water Resources Act*, which was mainly used as a tool for water allocation. The *Environmental Protection and Enhancement Act* also covers the treatment of groundwater for municipal supply.

Key points about groundwater protection from the *Water Act* (Province of Alberta, 1996):

- Top priority for water uses is for household purposes and does not require a license - it is a statutory right. The person must own or occupy the land on which groundwater exists. The right applies to a maximum of 1250 m³ of water per year per household. Water can be used for human consumption, fire protection, sanitation and watering animals, lawns, gardens and trees.
- Traditional Agricultural Users had the opportunity to voluntarily register their water use up to a maximum of 6250 m³ of water being used for pesticide application and/or raising animals.
- Under the *Water Act* a license for the diversion of groundwater is required unless used for household purposes, traditional agricultural purposes or falls under an exemption under the *Water (Ministerial) Regulations* (Province of Alberta, 1998). Licenses have a priority number and expiration date.
- Licensing and registration is based on "first in time, first in right" principle, where priority numbers are based on the date of first use of the water.
- Existing licenses in good standing were brought forward under the *Water Act*, when the Act came into force in 1999.

4.1.2 *Saline and Non-saline Groundwater*

Protection of groundwater under the *Water Act* applies to non-saline groundwater. Saline groundwater is defined within the *Water (Ministerial) Regulation* as water has a total dissolved solids concentration exceeding 4,000 mg/L. Stipulations under the *Water Act* that relate to saline

groundwater concern the protection of non-saline groundwater, such as ensuring that formations producing saline groundwater are sealed to prevent mixing with non-saline groundwaters.

Definitions of saline groundwater vary amongst the literature. For example:

- brackish water is defined as having a TDS concentration ranging from 1,000 to 10,000 mg/L, saline water from 10,000 mg/L to 100,000 mg/L, and brine is >100,000 mg/L (Freeze and Cherry, 1979; Fetter, 1994).
- Hem (1970) defines moderately saline groundwater as ranging from 3,000 mg/L to 10,000 mg/L.

The development of the definition used in Alberta to distinguish between saline and non saline water was largely related to the intended use of the water, in particular the tolerances for agricultural purposes (Section 3.2). A TDS concentration of 3,000 mg/L was initially considered, however it was recognized that there are several deep wells in Southern Alberta, which produce groundwater for stock watering purposes with a TDS concentration between 2,500 and 3,500 mg/L (Pretula, 1984). This groundwater should be protected under legislation. After discussions a TDS concentration of 4,000 mg/L was decided on. This selection was influenced by an Alberta Agriculture table entitled Chemical Analysis of Water for Livestock Use (Pretula, 1984), which indicated that water with a TDS of 4,000 – 5,000 mg/L is considered poor but “useable by cattle, sheep swine, horses and adult poultry”, and 3,000 mg/L to 4,000 mg/L was “fair water useable by animals except young poultry”. At this time, 4,000 mg/L was also considered to be the practical limit for treating water for household (domestic) use.

The Base of Groundwater Protection (BGWP) was established in Alberta defining the depth at which water becomes saline or exceeds 4000 mg/L. The water above the BGWP is protected and considered usable (Pretula, 1984). Using stratigraphic and hydrochemical data three formats for presenting the BGWP were developed. The three formats are:

- Reference Wells, which are specific wells with excellent geology and hydrochemistry data that can be used for industry to determine the depths for cementing and casing wells within the same township.
- Specific Depth is an area (township) where a specific depth is identified because geology is less defined. The depth is based on hydrochemical data.
- The Formation is the third format where there is little detailed geological or hydrochemical data so the BGWP is defined as the deepest geological formation known to contain useable groundwater.

4.1.3 *Additional Regulations and Policies*

Under the Guide 51 (1994) the Alberta Energy and Utilities Board (EUB) directs oil and gas operators to seal their wells from the BGWP up to surface to prevent intermixing of saline and non-saline groundwater. The EUB also requires industry to protect non-saline groundwater in well bores by using non-toxic drilling and fracturing fluids above the BGWP. Measures are also taken to ensure that if fracturing will occur above 200 meters there is no impact to water wells.

Industry is also required to test water wells, springs and dugouts within minimum of 600 meters radius of CBM wells completed above the BGWP.

With the fairly recent increase in CBM production in Alberta, a Multi-stakeholder Advisory Committee was formed. One document prepared by the Multi-stakeholder Advisory Committee concerns guidelines for groundwater diversion related to CBM developments (Multi-stakeholder Advisory Committee, 2004). This document is currently being enforced by the EUB and AENV in Alberta and addresses groundwater produced as a side product of CBM operations. Production and disposal of saline water (TDS>4,000 mg/L) is monitored by the EUB. The EUB monitors the quantities of saline water produced as a result of oil and gas activity, but it is not readily available public information (quantities can only be specified on a site specific basis) (pers. comm. Dickinson, 2007). AENV must authorize the diversion and use of any non-saline water. The EUB regulates disposal using injection wells. Water disposal is not allowed above the BGWP and disposal above 600 meters is subject to stringent guidelines. Before authorization is given by AENV, the applicant must demonstrate to AENV that the diversion or use of the non-saline groundwater will have no adverse effects on other groundwater users, or the aquifer itself (no aquifer dewatering) as part of the preliminary groundwater assessment. The preliminary groundwater assessment involves a fairly detailed investigation involving, hydrogeological cross-sections, field verified surveys, monitoring wells, aquifer testing, water quality analysis and public notice.

In 2002 AENV introduced a new approach to water management with the Water for Life: Alberta's Strategy for Sustainability (AENV, 2002). The strategy set-out to define specific long-term goals to improve Alberta's water management practices. The three main goals identified were:

1. Reliable quality water supplies for sustainable economy;
2. Healthy aquatic ecosystems; and
3. Safe, secure drinking water supplies.

In response to public concerns regarding the consumptive use of water by the oil and gas industry the Water Conservation and Allocation Policy for Oilfield Injection (Government of Alberta, 2006) was introduced. The intent of the policy was that "new projects within water short areas that propose to use non-saline water must demonstrate that every feasible option has been evaluated and any non-saline water resource use will prevent stranding oil reserves."

4.2 Other Provinces

4.2.1 Groundwater Classifications and Regulations

Regulations in other provinces do not appear to define a specifically-stated upper limit for groundwater protection, however, in some policy documents a reference to an upper limit of 4,000 mg/L is made. Most of these documents have to do with industrial use or disposal of groundwater. Alberta is in the forefront in terms of defining a base of groundwater protection. The Table 3 summarizes where the 4,000 mg/L value is referred to:

Table 3 Summary of Provincial Groundwater Document References to TDS

Province	Limit	Referenced in
British Colombia	"the total dissolved solids in the produced water immediately prior to discharge is less than or equal to 2 times the total dissolved solids in the underlying ground water...to a maximum of 4,000 mg/L"	Part 2, Section 4: Code of Practice for the Discharge of Produced Water from Coalbed Gas Operations (British Columbia Ministry of Environment, 2005)
Saskatchewan	"Water taken from any source having TDS in excess of 4,000 ppm" costs less per cubic meter than water taken from a source with a TDS concentration lesser then 4,000 parts per million.	Schedule A: Saskatchewan Watershed Authority – Industrial Water use charges (Saskatchewan Watershed Authority, 2005)
Manitoba	"The goal of the new regional assessment of potable groundwater defined as groundwater with a Total Dissolved Solids (TDS) less than or equal to 4000 mg/L..."	Regional Groundwater Assessment of Potable Groundwater in Southwest Manitoba

Neither Manitoba nor Ontario have a formal use of TDS concentration in any of the regulations (pers. comm. Betcher, 2007), however, the above information suggests informal recognition of a potable water definition that is the same as that used in Alberta. The British Colombia reference to 4,000 mg/L, is likely based on Alberta's regulation (pers. comm. Hicke, 2007) and strictly applies to produced water.

In British Colombia industry uses 55% of the groundwater, agriculture uses 20%, municipality's use 18% and rural domestic use make up the remaining 7% (Berardinucci and Ronneseth, 2002). British Colombia has undertaken aquifer classification for about 900 aquifers, and the aquifers are ranked (pers. comm. Carmicheal and Hicke, 2007). Classification is not based on specific water quality parameters, but the overall level of use and vulnerabilities of the aquifer (Berardinucci and Ronneseth, 2002). The British Columbia Water Act (Province of British Columbia, 1996) does not require groundwater use to be licensed, although withdrawals of more than 6,480,000 litres per day (75 litres per second) must be reviewed under the British Columbia Environmental Assessment Act (Province of British Columbia, 2002). Disposal of produced water from CBM operations is regulated under the Environmental Management Act. – Coalbed Gas Code of Practice (British Columbia Ministry of Environment, 2005; Province of British Colombia, 2006). Blending of brackish groundwater is not regulated.

In Saskatchewan, groundwater extraction is licensed; however groundwater quality for protection is not specified in any of the regulations. In practice, however, a streamlined approach is used for applications requesting to use brackish water from a known saline aquifer (the Colorado Group) (pers. comm. Shaheen, 2007). The groundwater branch of the Saskatchewan Watershed Authority has initiated a series of regional groundwater assessments (Saskatchewan Watershed Authority). The primary focus of these regional assessments is to provide summaries of the geology and hydrogeology, water quality, yield, use and potential contamination sources for individuals, rural and urban municipalities and industry. The use of blended groundwater is regulated by Saskatchewan Environment. Deep well injection is regulated in under the Oil and Gas Conservation Act (Saskatchewan Industry and Resources, 2003). Submission for approval for a waste disposal well is similar to Alberta.

In Manitoba many rural residents rely on groundwater for all of their domestic needs. Groundwater is also used for livestock watering, irrigation, and industrial processing, heating, and cooling (Government of Manitoba). In Manitoba non-domestic groundwater extraction over 25,000 liters per day (0.29 liters per second) requires a license. No aquifer classification system has been developed in Manitoba. They allow blending of brackish groundwater with fresh surface water to be used for municipal purposes (pers. comm. Betcher, 2007).

In Ontario permits are required to use over 50,000 liters per day (0.58 liters per second) of groundwater or surface water (Ministry of the Environment of Ontario, 2005a). A permit application must classify their water source into one of the three categories outlined in the permitting document. Category 1 is a low risk, such as renewing a permit where the Ministry has already evaluated the potential risks. Category 1 would also be takings less than 1 million liters per day (11.57 liters per second) from the Great Lakes or its connecting channels and meets the criteria listed in a table (Ministry of the Environment of Ontario, 2005b). The table mainly deals with volumes and surface water and groundwater interaction. It does not deal with water quality. Categories 2 and 3 have a greater potential risk which may require the submission of additional scientific studies. For example a category 2 water taking is "short-term, non-recurring taking less than 30 consecutive days and less than 400,000 liters per day (4.63 liters per second), such as construction de-watering or dust suppression" (Ministry of the Environment of Ontario, 2005b). A category 3 is the highest risk and does not fall into either of the previous categories.

4.3 United States

4.3.1 *Groundwater Classifications and Regulations*

The USEPA is charged with setting national standards for a variety of environmental programs and delegates to states and tribes the responsibility for issuing permits, monitoring and enforcing compliance. In 1986 the USEPA issued guidelines for groundwater classification as a follow up to the Ground-water Protection Strategy (USEPA, 1984). This guideline divides groundwater sources into three classes (USEPA, 1986), which determine the level of protection or remediation the resource will be provided. For example, a regulated activity over a Class I water source will have more stringent requirements compared to an activity over a Class III water source. The three classes are based on hierarchical categories on the basis of their value in society, use, vulnerability to contamination (USEPA, 1986) as outlined as follows:

Class I	Special groundwater. Irreplaceable sources drinking water and/or ecologically vital
Class II	Groundwater currently and potentially a source for drinking water. Drinking water is defined as having a TDS concentration less than 10,000 mg/L which can be used without treatment, or which can be treated using methods reasonably employed in a public water system
Class III	Groundwater not a source of drinking water. Saline or otherwise contaminated beyond levels which would allow use for drinking or other beneficial purposes.

The three class approach has been followed by other jurisdictions, i.e., individual states; however they have each adopted their own specific definitions for each class. For most states studied, the highest class defines non-saline, valuable groundwater that could be used for drinking water purposes without treatment. The lowest class is saline groundwater that is not considered useable or treatable for drinking water purposes. The second class falls somewhere in-between these. State agencies are not required to adopt this classification from the USEPA, however, these guidelines are applicable on all federal lands (USEPA, 1986). The USEPA approach has been used on Superfund sites and radioactive waste disposals for example.

Similar to the BGWP in Alberta, the USEPA has defined an underground source of drinking water (USDW). The USDW is an aquifer or its portion which: supplies drinking water for human consumption, or contains water with a TDS concentration of less than 10,000 mg/L (USEPA, 2002). This definition appears to be based on the livestock watering guidelines provided earlier in Table 2. A state can designate (and request approval from the USEPA) for some aquifers that meet criteria for USDW as exempted from this definition if they don't serve as a source of drinking water and are not expected to ever serve as a source in the future. Exemptions are granted for aquifers that contain commercial minerals (such as oil and gas) or for the purpose of injection. USEPA makes the final determination on all exemptions. USEPA also offers a chance for a public hearing, if the water in the aquifer has less than 3,000 mg/L concentration of dissolved solids.

4.3.2 *Additional Regulations and Policies*

The USEPA provides protection of drinking water sources with respect to groundwater injection through the Underground Injection Control (UIC) (USEPA, 2002). Minimum requirements established by the USEPA are adapted to state or tribe specific UIC programs. The UIC regulates the location, construction, operation and closure of injection wells to ensure safe disposal of hazardous fluids while protecting drinking water sources. Seven states share responsibility of implementing the UIC with the USEPA (including Florida, California and Montana), while most states have adopted their own (Texas, Wyoming, etc.).

The following summarizes the various classes of wells under the UIC program (USEPA, 2006):

Class I (Deep Wells) Class I wells dispose of industrial hazardous, non-hazardous and municipal (non-hazardous) waste. Class I wells are mainly used by petroleum refining, metal production, chemical production, pharmaceutical production, commercial disposal, municipal disposal and food production (USEPA, 2006). Currently the largest, most numerous and most sophisticated municipal Class I injection wells are in Southern Florida where favorable hydrogeological conditions make subsurface injection possible (pers. comm. Mickley, 2007).

Class II (Oil and Gas Injection Wells)	Class II wells exist wherever there is production of oil and gas. They are used for the re-injection of brine. Class II wells have to follow strict construction and conversion standards except when historical practices in the State and geology allow for different standards (USEPA, 2006).
Class III (Mining Wells)	A number of minerals are mined by using injection wells. EPA protects drinking water from contamination from mining wells by implementing regulations that set minimum standards (USEPA, 2006).
Class IV (Shallow Hazardous and Radioactive Injection wells)	These wells are prohibited unless the injection wells are used to inject contaminated ground water that has been treated and is being injected into the same formation from which it was drawn (USEPA, 2006).
Class V (Shallow Injection Wells)	Class V wells are used for storage or disposal of non-hazardous fluids into or above the USDW. The fluid injection must meet appropriate criteria as determined by the classification of the receiving aquifer. Common types of Class V wells include air conditioning return flow wells, swimming pool drainage wells, storm water drainage wells, lake level control wells, domestic waste wells and aquifer storage and recovery (USEPA, 1980).

Hazardous wastewater must be injected below the USDW through well Classes I through IV (USEPA, 1980). Examples of waste include produced high saline brine, crude oil (for storage), radioactive waste or treated municipal effluent.

The fundamental purpose of the UIC program is to protect current drinking water sources mixing with hazardous waste from injection due to five identified pathways: faulty well construction, nearby wells, faults or fractures in confining strata, direct injection, and displacement (hydraulically connected USDWs). To prevent contamination, these wells must be completed to certain standards, including monitoring and testing requirements. The tuber and packer arrangement required for all injection wells other than non-corrosive municipal waste injection is the most costly factor in deep well injection (pers. comm. Mickley, 2007).

Some states have established UIC programs but do not allow underground injection of industrial wastes including membrane concentrate because of unfavorable conditions.

Concentrate disposal falls under various acts and under federal law is regulated as an industrial waste. In Florida however, they have defined potable water byproduct and with this a committee has formed that is working on special regulations and permits required for concentrate disposal. The five main concentrate disposal methods (discussed in detail in section 4.0) and applicable legislation are summarized in Table 4.

Table 4 **Summary of Concentrate Disposal Regulations (Mickley, 2001)**

Disposal Method	Applicable regulations
Surface discharge	NPDES (CWA), state and local regulations
Disposal to WWTP	state and local regulations
Land Application	state and local regulations
Deep Well injection	NPDES (CWA), SDWA (UIC), state and local regulations
Evaporation ponds	NPDES (CWA), state and local regulations

Notes: WWTP is a waste water treatment plant
 NPDES is the National Pollutant Discharge Elimination System
 CWA is the Clean Water Act, regulations mostly related to effluent
 SDWA is the Safe Drinking Water Act, regulations mostly related to water quality

The regulations for disposal to surface water ensure that the water quality is maintained for its intended use. Under the Clean Water Act each state is required to set water quality standards for its water bodies (Mickley, 2001). Drinking water standards are used as the water body standards in some instances. There are national limitations and standards for all facilities that discharge or may discharge directly into waterways or that indirectly discharge or may discharge into publicly owned treatment works (Mickley, 2001). Any direct discharge must have a National Pollutant Discharge Elimination System ("NPDES") permit, which specifies the permissible concentration or level of contaminant in a facility's effluent. In addition to water quality parameters a reverse osmosis (RO) facility must pass a program called Whole Effluent Toxicity, which has been used as a regulatory tool since the 1970's (Mickley, 2001). Basically bioassays and biomonitoring are carried out on the species living in the receiving waters. Toxicity endpoints are considered to be acute, chronic or both (Mickley, 2001). Obtaining a permit involves many forms and information regarding flows, effluent quality, treatment systems etc., plus public review.

Disposal of membrane concentrate to a waste water treatment plant does not require a permit. It is the responsibility of the waste water treatment plant itself. Some treatment facilities require pre-treatment so the facility can meet its water quality guidelines and a fee usually applies (pers. comm. Mickley, 2007)

Land application and evaporation ponds may require permits on a site specific basis. It mainly depends on if there is a potential risk that leakage to a surface water or drinking water aquifer could occur. Secondary containment or proof that there is no possibility of transmission to the receiving water is required.

4.3.3 *Wyoming*

4.3.3.1 Groundwater Classifications and Regulations

Eighty per cent of residents in Wyoming depend on groundwater for its drinking water supply. The Department of Environmental Quality (DEQ) in Wyoming issued a Quality Standards for Wyoming Groundwater Chapter of the Water Quality Rules and Regulations in 2005. The Standards classifies groundwater in order to protect the natural quality of underground waters. This classification is quite different from other states and federal regulations and is classified by

use, and by ambient water quality (not solely based on TDS). One issue the DEQ in Wyoming identifies with the federal classification system is that it does not account for any other constituents “Using this (*federal*) definition, an aquifer containing 7 mg/l of Arsenic (which would be toxic to drink) would still be a USDW if the TDS content was less than 10,000 mg/L” (DEQ, 2004). This explains why Wyoming has adopted their own classification system, which provides maximum concentrations for a variety of parameters.

- | | |
|-------------------|---|
| Class I | Groundwater suitable for domestic use. These waters are classified by a list of water quality standards for metals, physical parameters (including TDS) and radioactive parameters. The maximum allowable concentrations are similar to the USEPA standards for drinking water for most parameters. TDS maximum allowable concentration is 500 mg/L. |
| Class II | Groundwater suitable for agriculture. This is qualified not only by water quality including maximum allowable concentrations listed in the Standards but also by other factors (DEQ, 2005). Parameters are again chemical, physical and radioactive. TDS maximum allowable concentration is 2000 mg/L. |
| Class III | Groundwater suitable for livestock. Qualifies based on the list of parameters, including chemical, physical and radioactive, in a table. TDS maximum allowable concentration is 5000 mg/L. |
| Class Special (A) | Groundwater suitable for fish and wildlife. Qualifies based on the list of parameters (chemical, physical and radioactive) in a table. Many parameters are most stringent for this class, as compared to other classes. TDS concentration is broken down into a maximum concentration of 500 mg/L for egg hatching, 1000 mg/L for fish rearing and 2000 mg/L for fish and aquatic life. |
| Class IV | Suitable for industry. Class IVA is when TDS concentrations are not greater than 10,000 mg/L, and Class IVB is when TDS concentrations are in excess of 10,000 mg/L. |

The regulations stipulate that a discharge into formations bearing any of these classes “shall not result in biological, hazardous, toxic or potentially toxic materials or substances including pesticides, insecticides or herbicides in concentrations, based upon information of the USEPA in the Federal Register for December 24, 1975 (Part IV), Water Programs, National Interim Primary Drinking Water Regulations, and in the Federal Register for March 13, 1978 (Part II), Water Programs, Hazardous Substances; or which exceed background concentrations of the under groundwater, whichever is greater, at any place or places of withdrawal or natural flow to the surface”. Class IV only refers to federal guidelines while Classes I through Special A have specific guidelines tabulated in the state regulations.

Class V This class is divided into three areas. Class V (hydrocarbon commercial), Class V (Mineral Commercial) or Class V (Geothermal). Class V (Mineral commercial) must “be returned to a condition and quality consistent with the pre-discharge use suitability of the water”. The other two class V divisions are mostly concerned with the protection of other resources. Discharge to Class V (Hydrocarbon Commercial) and Class V (Geothermal) “shall not result in the degradation or pollution or waste of other water resources”.

Class VI This is groundwater that is considered not suitable for use.

Interestingly Class VI is groundwater not considered usable, by the following standards:

- “(A) Due to excessive concentration of total dissolved solids or specific constituents; or
- i. Is so contaminated that it would be economically or technologically impractical to make the water useable; or
 - ii. Is located in such a way, including depth below the surface, so as to make use economically and technologically impractical”

In practice a Class VI is usually a groundwater that is contaminated by hydrocarbons or contaminants other than TDS, so as to not confuse it with a Class IVB (pers. comm. Fredrich, 2007).

This classification is primarily based on use, then on water quality. For example, in an area where there are no wells within approximately 1 mile the classification is based strictly on the water quality compared to the Standards (DEQ, 2005), however in an area that has mostly domestic wells, even if a parameter exceeds the Standards the groundwater is protected to its ambient quality and is still protected as a Class I well (pers. comm. Fredrich, 2007).

Classifications are given to aquifers which are described by lithology and extent, “based on existing water use, ambient water quality and geological and hydrological characteristics of the aquifer or of the receiver”. Aquifers will be classified when there is “pollution or the threat of pollution to a groundwater of the state” or “the physical, chemical, radiological or biological properties of any groundwater of the State are or may be altered by man’s action”.

More generally the Water Quality Rules and Regulations specifies that no matter what class of groundwater quality, activities “shall not result in the water being unfit for its intended use” or have a toxic effect on biota. Any discharge to a groundwater aquifer shall not impair the water quality in excess of the standards. This classification system mainly deals with the protection of groundwater, rather than management of use. Permits for groundwater extraction must be approved by a state engineer, where well construction details and well use are specified (pers. comm. Fredrich, 2007). The quality of the groundwater source is not linked to its purpose, for example an industrial user can use fresh groundwater; however a regulation regarding this is likely forthcoming (pers. comm. Fredrich, 2007).

The only issue identified by regulators was that industrial users must protect water even if it is very low producing (pers. comm. Fredrich, 2007). The regulations currently interpret water in the vadose zone or moisture in the soil as protected groundwater. Wyoming is considering establishing a minimum volume of water for protection.

4.3.3.2 Additional Regulations and Policies

In Wyoming the state adapted the UIC program (as opposed to the USEPA). The UIC program has defined five classes of injection facilities as shown in Table 5 below:

Table 5 Summary of Wyoming UIC Program (DEQ, 2005)

Class of Injection	Type of facility
I	Deep disposal of industrial, commercial or municipal waste below the deepest usable aquifer. This type of injection always uses wells and usually requires applied pressure. Includes all wells which dispose of waste on a commercial basis, even if the waste disposed of would be otherwise eligible for disposal into a class II well.
II	Deep disposal of wastewater produced in conjunction with the production of oil and gas.
III	Injection wells for the purpose of recovery of minerals. Includes the experimental technology wells, underground coal gasification wells, in situ mining wells for the recovery of copper, uranium, etc.
IV	Illegal facilities which disposal of hazardous waste into or above any useable aquifer. The only wells in this category are used to re-inject treated groundwater that was previously contaminated as part of remediation. Groundwater must be re-injected to the same aquifer it was taken from.
V	All other facilities which dispose of fluids into the subsurface, including CBM produced water

Class I wells are not permitted to inject hazardous waste in Wyoming. To avoid duplicating regulatory powers, the DEQ governs over all oil and gas production waste injection as a class I under their jurisdiction.

4.3.4 Montana

4.3.4.1 Groundwater Classifications and Regulations

TDS concentrations in the western half of Montana do not usually exceed 300 mg/L and the eastern side usually exceeds 1,000 mg/L (Ground Water Protection Council, 1999). Montana regulates groundwater using a similar approach to Wyoming. The Montana Groundwater Pollution Control System Regulations (State of Montana, 2006) classifies groundwater into Classes I through IV based on the present and future most beneficial uses of the groundwater and states groundwater is to be classified to actual quality or actual use, whichever places the groundwater in a higher class. The classes are summarized below (State of Montana, 2006):

Class I	Groundwater which natural specific conductance less then or equal to 1,000 microSiemens per centimeter at 25°C. Water quality must be maintained so that water is suitable for: public and private water supply,
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culinary and food processing purposes, irrigation, drinking water for livestock and wildlife, commercial and industrial purposes. The regulations refer to water quality parameters called the human health standards and any parameters not listed in the standards are not allowed to increase in a level that “renders the waters harmful, detrimental or injurious to the beneficial uses listed for class I waters”.

- Class II Waters have a specific conductance between 1,000 and 2,500 microSiemens per centimeter at 25°C. The quality of water has to remain at least “marginally suitable” for the same uses as in Class I, and must follow the human health standards as well and not cause degradation of the water quality
- Class III Groundwaters have a specific conductance between 2,500 and 15,000 microSiemens per centimeter at 25°C. Again the groundwater must remain marginally suitable, however only for “(i) irrigation of salt tolerant crops, (ii) some commercial and industrial purposes, (iii) drinking water for some livestock and wildlife, (iv) drinking, culinary and food processing purposes where the specific conductance is less than 7,000 microSiemens per centimeter at 25°C”. (State of Montana, 2006). Again Class III waters must adhere to the human health standards; however there are some exceptions with nitrate levels.
- Class IV Waters have a specific conductance greater than 15,000 microSiemens per centimeter at 25°C. The quality must be maintained so as to be suitable for some industrial and commercial uses. The only human health standards that apply to a Class IV are the ones classified as carcinogenic. Degradation can not occur to Class IV water so as to adversely affect existing beneficial uses. Other nondegradation clauses do not apply to Class IV waters.

The regulations require that “any groundwater whose existing quality is higher than the standard for its classification must be maintained at that high quality unless degradation is allowed” under the nondegradation rules (State of Montana, 2006).

4.3.4.2 Additional Regulations and Policies

Montana follows the federal UIC program.

4.3.5 *North Carolina*

4.3.5.1 Groundwater Classifications and Regulations

In North Carolina groundwater quality is classified into three classes (Department of Environment and Natural Resources Division of Water Quality, 2005).

Class GA	Groundwaters containing 250 mg/L or less of chloride. This Class is suitable for drinking water in its natural state.
Class GSA	Groundwaters naturally containing chloride concentrations greater than 250 mg/L, but otherwise suitable for drinking water after treatment. The Standards (Department of Environment and Natural Resources Division of Water Quality, 2005) for Class GSA are the same as GA, but: • Chloride: allowable increase not to exceed 100% of the natural quality concentration • TDS: Must be less than 1000 mg/L
Class GC	Does not meet the Standards for Class GA or Class GSA, efforts to improve would not be technologically feasible. Consumption of this water would cause adverse effects on humans.

The purpose of this classification is mainly for protection, with respect to contaminated sites. Zones classified as GC can not migrate into Class GA or Class GSA zones, for example. It is interesting to note the use of chloride concentrations in these definitions as opposed to TDS.

4.3.5.2 Additional Regulations and Policies

In North Carolina there are several membrane utilities (approximately 20 to 50) with a few large reverse osmosis systems on the coast (Mickley, 2001). The State is issuing new membrane disposal guidelines.

4.3.6 Texas

4.3.6.1 Groundwater Classifications and Regulations

The state has classified groundwater into four classes based on TDS concentration as outlined in Table 6.

Table 6 Summary of Texas Groundwater Classification System (Adapted from Texas Groundwater Protection Committee, 2003)

Class	Quality (TDS in mg/L)	Examples of Use	Agency Response
Fresh	0 to 1,000	Drinking and all other uses	Level I Response: Protection or restoration measures based on current or potential use as a human drinking water supply (response considers water quantity as well as quality)
Slightly Saline	1,000 to 3,000	Drinking (if fresh water is unavailable), livestock watering, irrigation, industrial, mineral extraction, oil and gas production	
Moderately Saline	3,000 to 10,000	Potential/future drinking and limited livestock watering and irrigation (if fresh or slightly saline water is unavailable), industrial, mineral extraction, oil and gas production	
Very Saline to Brine	> 10,000	Mineral extraction, oil and gas production	Level II Response: Protection or restoration measures based on indirect exposure or no human consumption

This water quality classification is used to identify which aquifers have useable water. This classification is a guide for the state groundwater protection program and can be used for specific activities, such as “surface casing and cementing requirements for oil and gas production wells for aquifers with TDS concentration of less than 3,000 mg/L” (Texas Groundwater Protection Committee, 2003). This classification is a guideline and not specified in any regulations. The United States Geological Survey and the USEPA use a similar classification. Texas has prepared maps showing the downdip boundaries of aquifers along the 3,000 mg/L TDS line in recognition of the irrigation and industrial uses for the aquifers (pers. comm. Kalaswad, 2007).

The Texas Commission on Environmental Quality issued a Groundwater classification guide bulletin (Groundwater Services Inc., 2003) that defines groundwater classes slightly differently from the above classes. The guide is used for persons conducting Affected Property Assessments (sites where groundwater bearing units are “affected or potentially affected”). Basically the level of clean-up on one of these sites reflects the class of groundwater it may affect. The classes are based on I) the current use of the groundwater resource within a half mile radius around the affected groundwater zone and II) the potential use of the groundwater resource, as determined by its salinity and sustainable well yield. The lower the class the more vulnerable the groundwater resource is to contamination.

Class 1 Primary Resource where the affected groundwater zone could impact existing public water supply within a half mile. The groundwater-bearing unit is the only reliable source of water in the area, or the groundwater-bearing unit is capable of producing 100 gallons per minute from a single 12-inch diameter well with a TDS concentration of 3000 mg/L or less and meeting all Primary Drinking Water Standards.

- Class 2 Potential Resource, qualifies if the contaminated groundwater could impact an existing non-public source within a half mile or is capable of producing greater than 150 gallons per day from a single 4-inch diameter well with TDS of less than 10,000 mg/L.
- Class 3 Non-potential Resource. There is no water supply of any kind within a half mile, or the groundwater-bearing unit is low producing (less than 150 gallon per day), with a TDS concentration of less than 10,000 mg/L.

A detailed flow chart of how the class is to be determined is provided in the bulletin.

In the Texas Administrative Code, Code 40, Parts 144 to 146 (Texas Groundwater Protection Committee, 2003) define groundwater contamination for the purpose of enforcement. Groundwater contamination applies to affected groundwaters with a TDS concentration less than or equal to 10,000 mg/L, and greater than 10,000 mg/L if it is:

- “a) currently extracted for beneficial use such as domestic, industrial or agricultural purposes; or
- b) hydrologically connected with, and with the potential for contaminant movement to, a surface water body or another zone of groundwater which has a concentration of less than or equal to 10,000 mg/L of TDS”

(Texas Groundwater Protection Committee, 2003).

Individual groundwater conservation districts manage groundwater at a local level and manage aquifers on a regional basis where multiple districts overlie a common aquifer (pers. comm. Kalaswad, 2007). Groundwater permits (for groundwater extraction) can be issued by a groundwater conservation district, but they have limited authority. Texas’ guiding principle for the management of groundwater is the Rule of Capture. Under this rule, a landowner may pump unlimited amounts of groundwater for a beneficial purpose without any liability to surrounding landowners. The rule of capture is a topic of continuing debate in Texas.

4.3.6.2 Additional Regulations and Policies

In terms of concentrate disposal the various disposal options for Texas involve state or federal permitting. Land irrigation only requires a permit if greater than 5000 gallons per day in which case it requires a Texan Pollutant Discharge Elimination System permit. Sludge disposal and surface discharge also requires a permit. Disposal of salts to a landfill is regulated under the Texas Commission of Environmental Quality. Deep well injection is not a common practice, but requires a UIC permit.

4.3.7 *Florida*

4.3.7.1 Groundwater Classifications and Regulations

Florida relies on groundwater for 87% of its drinking water (Department of Environmental Protection, Florida, 2004). So they are a natural leader in protecting this resource. The Floridian aquifer is a major source of drinking water for all but the westernmost and southernmost parts of

the state. TDS concentrations are from 1,800 mg/L to 5,000 mg/L, so protecting groundwater with salinities higher than drinking water guidelines is important.

Groundwater Standards are used to provide a framework for the state's various ground water protection programs and to protect groundwater used for potable water supply as well as a reference to determine when contamination occurs. The classes are defined as follows (Department of Environmental Protection, 2004):

Class F-I	Potable water. Groundwater in a single source aquifer that has a TDS content less than 3,000 mg/L and was specifically reclassified as Class F-1 by the Environmental Regulation Commission.
Class G-I	Same as above, but not reclassified by the Environmental Regulation Commission.
Class G-II	Same as above with TDS less than 10,000 mg/L.
Class G-III	Not potable. Groundwater in unconfined aquifers with TDS greater than 10,000 mg/L. Or TDS is between 3,000 and 10,000 mg/L and has either been reclassified as having no reasonable potential as a future source of drinking water, or has been designated as exempted aquifer.
Class G-IV	Not potable. Groundwater in confined aquifers with TDS greater than 10,000 mg/L.

4.3.7.2 Additional Regulations and Policies

Florida has extensive regulatory requirements for utilities using membrane technology (Mickley, 2001). In Florida there are six regulatory districts in charge of issuing permits (NPDES) for discharge of wastewater into waters of the state (including groundwater). The water quality standards depend on the class of water body the membrane concentrate is entering. Class II waters are dedicated to fisheries activities and have more requirements than Class III waters which are recreational waters. Deep well injection requires a Class I injection well disposal of non-hazardous concentrate permit, which includes well identification, depth, casing volume, allowed pressure and required monitoring wells (Florida Department of Environmental Protection). Land application is a permitted practice that is used and blending is common to bring the TDS concentration down. Blending ratios are detailed in the permit. Protection of groundwater from holdings ponds is also included in the required permit, which specifies monitoring requirements.

4.3.8 California

4.3.8.1 Groundwater Classifications and Regulations

California uses more groundwater than any other state. California has no statewide groundwater management plan or strategy and groundwater appears to be governed on a local level (Bachman et

al., 2005), however desalination projects are regulated by the state. California is addressing a need to govern its resources more effectively, with a seemingly unlimited number of claims to groundwater. The state recognizes the need for desalination and that desalination projects are given the same opportunity for funding as other water supply projects (State of California, 2003). Recently Governor Schwarzenegger amended the Urban Water Management Planning Act to adopt urban water management plans including a description of the opportunities for the development of desalination water including brackish groundwater (Karajeh and BenJemaa, 2004)

4.3.8.2 Additional Regulations and Policies

In terms of concentrate management California has a permit system for membrane waste disposal similar to the NPDES. In terms of disposal options, evaporation ponds are not a common practice, however if used they must comply with the maximum contaminant level requirements. Land application is available in some regions but requires meeting water quality requirements. California has a UIC program for deep well injection. Disposal to a publicly owned treatment works is an option with the receiving work monitoring effluent loads. Any whole effluent toxicity requirements are tailored to the receiving water ecosystem. There are no special requirements for the water treatment plants using membrane technology. Concentrate and sludge disposal is not subject to any unique regulations other than those required for any wastewater disposal.

4.4 International

India, Pakistan, Bangladesh, China, Spain and Mexico all extensively use groundwater. These countries along with the United States together use over 65-70% of the 800 cubic kilometers of groundwater extracted annually (Mukherji and Shah, 2004). In many countries the limitations to groundwater use are typically practical, i.e., related to the cost of pumping equipment or well installation. One response to these financial limitations has been the use of informal water markets, which can be found in India, Pakistan and Bangladesh. The markets function uninterrupted by any regulatory authority. The only point of contact between the regulators and the water markets is the electrical utility.

4.4.1 China and South Asia

In South Asia groundwater can be extracted as much as desired as established under the English Law (Mukherji and Shah 2005). The rights to groundwater are attached to the land so a landowner has no restriction on water quantity. In much of South Asia a top priority had been attaining food self-sufficiency. The potential for increased food production is often found by using groundwater for irrigation. Policy makers have therefore often chosen to avoid imposing regulations that may limit groundwater use.

In China the price of water is regulated, unlike in the rest of South Asia. Some attempts to slow water depletion were the adoption of micro-irrigation and the elimination of paddy cultivation in China. Groundwater governance has changed from that of being highly fragmented to that of being more institutionalized and decentralized (Mukherji and Shah, 2004). China has a National Water Law that was enacted in 1988 (Chinese Government, 2002). Under the Chinese National

Water Law, groundwater extracted for domestic, livestock or other small uses does not require a license. Article 25 "In areas which are prone to salinization-alkalization and water-logging, measures shall be taken to control and lower the groundwater level". Article 30 and 36 deals with groundwater protection. The three main points are:

- A plan must be in place before the drawing of groundwater is allowed based on an investigation into groundwater resources.
- In areas where too much groundwater has been drawn a control can be installed.
- One cannot deplete someone else's groundwater resource.

4.4.2 *India*

Draft bills for regulating water have been debated for decades in Pakistan and India, but known difficulties in implementation have prevented them from being made into law. A study conducted in a south west district of National Capital Territory of Delhi, India (Shekhar, 2006) suggests that in this scarce water district groundwater protection is only being considered now. Fresh water in this article is considered to have an electrical conductivity less than 1500 microSiemens per centimeter at 25°C. The authors recommended in their conclusions that shallow saline groundwater be applied to crops and used for "other domestic" uses, reserving deeper fresh groundwater for drinking water, as part of a dual water supply system. The study microzoned the district to determine the thickness of fresh water and identified potential freshwater zones for future use.

4.4.3 *Denmark*

In 1998 the government of Denmark classified the country into three types of groundwater: particularly valuable, valuable and less-valuable (Thomsen et al., 2004). The classification is based on water quality and quantity. The government of Denmark has taken on a 10-year plan to further classify groundwater resources based on vulnerability, in order to facilitate protection of the groundwater resource in order to meet future water-supply demands (Thomsen et al., 2004).

4.4.4 *Spain and Mexico*

Both Spain and Mexico have formal legislation regarding groundwater; the Water Act of 1985 and the Law of Nation's Water of 1992, respectively (Mukherji and Shah, 2005). Both require groundwater extraction permits, and both have some regulations to protect and restore over exploited aquifers. Both countries have had issues with identifying and recording groundwater users. In Mexico a subsidy for electrical power and in Spain a compensation scheme are working to encourage well registration.

4.4.5 *Jordan*

Currently in Jordan groundwater aquifers are exploited at more than double their sustainable yield (International Development Research Center). A study conducted in Jordan, found that there is a need to regulate the use of brackish groundwater due to an extreme demand for its potential use (Al-Hadidi, 1999). In the study brackish groundwater is considered to fall between

1000 to 10,000 mg/L. The study first identified sources of brackish water in the Jordan valley. According to this study the "quality, quantity and location of this resource should be carefully studied in order to assess future brackish water development and management" (Al-Hadidi, 1999). Some policies that touch on the use of desalinized brackish water include the Economic and Social Development Plan (1993–1997) and the Treaty of Peace (1994). The later policy mainly deals with saline springs identifying the portions of which Jordan is entitled to. The former document regulates the use of ground and surface water for various purposes by assessing the quantity and the quality of brackish groundwater. Further details on this policy could not be found however despite these policies the study reveals that there is an absence of policies, laws and regulations for brackish water use and management (Al-Hadidi, 1999). There is also a lack of guidelines and a standard regarding the possible use and methods of disposal of brine, as Jordan looks at installing more desalination plants. The study recommends that agriculture and industry use brackish water, reserving fresh water for other purposes.

4.5 Summary of Groundwater Classifications and Regulations in Canada and United States

Table 7 summarizes the available information regarding groundwater classification and regulations within the provinces and states included in this study. Blank cells indicate information that was not identified through the review.

All provinces and states protect groundwater, but not all use a classification system. Groundwater classification systems appear to be primarily intended for protection purposes rather than for management of use. Information for groundwater uses in the states is interpreted to include all groundwater with a TDS of 10,000 mg/L with saline uses also noted.

Table 7 Summary of Groundwater Classifications, Regulations and Use in Canada and the United States

Province/ State	Basis for Aquifer Classification	Quality Parameters in Definition	Intention of Classification	License Procedure?	General Groundwater Uses ^{iv}	Brackish Water Treatment Facilities
British Columbia	Degree of use and vulnerability	N/A	Protection	No	Industry, agriculture, municipalities, rural domestic	No
Saskatchewan	No Classification	N/A	N/A	Yes – differential process/charge for water with TDS > 4,000 mg/L	Municipal and industrial identified	Yes
Manitoba	No Classification	N/A	N/A	Yes	Rural domestic, livestock watering, irrigation, and industrial processing, heating, and cooling	Yes
Ontario	No Classification	N/A	N/A	Yes	unknown	
Wyoming	Use (primary) and water quality (secondary)	Various (chemical, physical and radioactive)	Protection	Yes	Drinking water, industry, agriculture (use of saline in mining)	
Montana	Use and Quality (most conservative)	Specific Conductance	Protection		Irrigation, Public drinking, industrial, domestic, livestock (use of saline in mining)	
North Carolina	Quality	Chloride	Protection		Domestic, public supply, livestock, industrial, irrigation	
Texas	Quality	TDS	Protection	Yes	Irrigation, public supply	Yes
Florida	Quality	TDS	Protection		Public supply, irrigation, industrial, domestic, mining (use of saline in mining)	Yes
California	No Classification	N/A	N/A		Irrigation, public supply, industrial (use of saline in mining and industry)	

N/A – Not applicable

^{iv} Information for United States uses came from USGS 1995. Uses are listed in descending order of percentage used.

5.0 TREATMENT TECHNOLOGY FOR BRACKISH GROUNDWATER

5.1 Introduction

Fresh water resources in Alberta are becoming increasingly limited due to existing use and a growing demand. The use and development of non-conventional water resources such as brackish water could be a possible solution to overcome the potential shortages of fresh water. The poor quality of brackish water presents an obstacle; however, utilization of appropriate desalination technologies could help to make use of these low-quality groundwater resources.

Some of the potential benefits of desalination include:

- Increased and diversified sources of potable water;
- Conservation of natural fresh groundwater resources; and
- A viable alternative to withdrawing fresh groundwater.

Some of the potential constraints include capital, operating and production costs, environmental concerns, disposal of brine, and energy consumption.

Current technologies/methods that have been developed for the desalination of brackish groundwater include the following:

- Distillation techniques;
- Membrane processes; and
- Alternative methods such as freezing, hybrid thermal and membrane methods, and blending.

Distillation and membrane processes are the most common desalination methods in current use.

Concentrate management presents an additional challenge in places such as Alberta, where disposal of post-treatment concentrate to the oceans is not an available option. Some concentrate management options described in the literature include:

- Disposal to surface water;
- Disposal to sewer;
- Land application;
- Evaporation ponds;
- Deep well injection;
- Zero liquid discharge (production of solid product for landfill disposal); and
- Blending with wastewater for treatment or partial reuse/recycling.

In this section, the various desalination and concentrate management systems that are available will be described, their perceived benefits and limitations will be weighed, applicability in the province of Alberta will be assessed, and economic factors and costs for the methods will be compared.

5.2 Desalination Technologies

Processes for treatment of impaired waters have been available for many centuries. Traditionally, distillation has been the method used for desalting water for human consumption or other uses, but membrane methods have emerged through the last 50 years and now predominate among the desalination practices. The following describes each of the various methods used for water desalination treatment.

5.2.1 Distillation Methods

The Process:

There are several variations in distillation technology used in desalination. They are all based on the vapourization of liquid water when brought to its boiling point. The nearly pure water vapour produced is condensed and collected for use, while dissolved salts remain behind in the remaining liquid feed water. Some of the methods by which distillation is practiced are as follows:

- multi-stage flash;
- multiple effect;
- vapour compression;
- membrane distillation; and
- solar humidification.

The Benefits:

Modern distillation techniques have been in use for over a century, and have undergone many improvements over time. Distillation is most suitable for large capacity plants and high salinity feed waters (they are mostly used in seawater applications). Steam produced from conventional distillation methods can be used to generate electricity in dual-purpose facilities which can reduce costs (cogeneration).

The Major Issues/Constraints:

The biggest limitation concerning distillation processes is the large amounts of energy used to heat feed water. They are mostly impractical for brackish water applications since the amount of salts removed for the amount of energy consumed is much lower. The relatively high temperatures of operation are also conducive to scale/deposit formation on critical equipment.

In the following sections, brief descriptions of the principle distillation methods are given.

5.2.1.1 Multi-Stage Flash

In the multi-stage flash process, saline water is heated and introduced to a series of vessels where the ambient pressure is lower, thus causing the water to boil rapidly and generate steam. Feed water is passed from one stage to the next to be boiled repeatedly without adding heat. The steam produced is converted to fresh water through condensation on heat exchange tubes that run through each stage. The tubes are cooled by incoming feed water, which through the exchange of heat energy, slightly increases the temperature of the feed water, thereby reducing the amount of energy required to raise the temperature of the feed water prior to entering the depressurization vessels.

5.2.1.2 Multiple Effect

Multiple effect distillation was, for a time, displaced by multi-stage flash process because of the latter's better resistance to scaling of tubes and other metal surfaces. In the 1980's multiple effect distillation was revived, with new designs considered upon the concept of lower operating temperatures, thus reducing precipitates of carbonates and sulfates (Buros, 2000).

In this process, feed water is distributed on to an evaporator surface after being preheated to a boiling temperature. The surfaces in the first stage or "effect" are heated with steam from a boiler or steam turbines from a power plant. The steam is condensed on a colder surface within the effect. Condensate is recycled to the boiler for reuse. The surfaces of all other effects are heated by steam produced in the one preceding it, to condense the progressively more saline feed water. In the final effect, steam is condensed in a heat exchanger which is cooled by incoming feed water.

5.2.1.3 Vapour Compression

Vapour compression is often used in combination with other processes, and by itself for small and medium-sized plants. The heat for evaporating the water comes from the compression of vapour rather than direct exchange of heat from steam, thus reducing energy requirements. Steam ejectors and/or mechanical compressors are used to run the process. There are a variety of configurations. Most small plants only have one stage, whereas larger plants will have several. Vapour compression units are often used for resorts, industries and drilling sites where fresh water is not readily available.

5.2.1.4 Membrane Distillation

Membrane distillation was introduced in the 1980s, but did not yield any commercial success (Buros, 2000). This process involves heating of saline feed water for vapour production, with the resultant vapour subject to a membrane that allows the passage of vapour but not liquid water. After the vapour passes the membrane, it is condensed and the trapped liquid water is collected.

5.2.1.5 Solar Humidification

Solar humidification involves the use of a solar still to heat saline water in a basin with direct solar energy, thus reducing energy requirements and associated costs. The resultant water vapour is condensed on a cool surface, such as a sloping glass roof, and collected as fresh water product.

The drawbacks to this method are the limitations in scale due to land area requirements, as well as maintenance difficulties (Buros, 2000).

5.2.2 *Membrane Technologies*

The Process:

Membrane processes involve passing of impaired feed water through a semi-permeable material which can filter out unwanted dissolved or undissolved constituents, depending on the size and treatment of the openings. Membrane technologies identified in our literature review include:

- Reverse Osmosis;
- Microfiltration/Ultrafiltration/Nanofiltration;
- Electrodialysis Reversal; and
- Forward Osmosis.

The Benefits:

Membrane technologies have much lower energy requirements than thermal distillation methods. They are also the most suitable for brackish water applications.

The Major Issues/Constraints:

Membranes can be prone to “fouling” due to scale formation and entrapment of solid particles, so an additional pretreatment step is often required.

5.2.2.1 *Electrodialysis/Electrodialysis Reversal*

Electrodialysis was introduced for commercial use in the 1960's, and provided a more cost-effective way to desalt brackish water (Buros, 2000). It operates on the principle that dissolved ions, being positively or negatively charged, can be separated by introducing a direct electrical current source and a pair of electrodes. The ions will tend to migrate to the electrode carrying the opposite electrical charge (positive or negative).

The electrodes work in combination with membranes that allow selective passage of anions or cations. Water is passed between the electrodes, and ions migrate toward the electrodes of opposite charge. Anions pass through a cation selective membrane toward the positive electrode, while cations pass an anion-capturing membrane to get to the negative electrode. Spacers channel away the dilute product water and concentrate waters, which are now separated by the membranes.

A typical Electrodialysis unit consists of the following:

- Pretreatment to remove solid particles that can clog membranes;
- Stacks of membranes/electrode pairs;
- Low-pressure circulating pump;

- Power supply for direct current; and
- Post-treatment to stabilize the water, remove unwanted gases, and adjust pH.

Electrodialysis Reversal (EDR) is a variation whereby both the product and concentrate channels are identical in construction. Several times per hour, the polarity of the electrodes is reversed, and flow is simultaneously switched so that the product water channel becomes the concentrate channel and vice versa. The reversal is used to flush scales, slimes and other deposits that can build up, thereby reducing reliance on pretreatment, and minimizing membrane fouling.

5.2.2.2 Reverse Osmosis

Reverse Osmosis is a relatively new method which came into wider commercial use in the 1970s. RO is a process by which water from a pressurized saline solution is separated from solutes by passing through a membrane. The only energy required for desalination is in pressurizing the feed water.

In practice, the feed water is pumped into a vessel where it is pressurized against the membrane. A portion of the water passes through the membrane, while the remainder increases in salt content. To prevent precipitation of salts and increased osmotic pressures, a portion of the feed water is discharged without passing through the membrane. The basic components include:

- Pretreatment to remove suspended solids and prevent microbial growth;
- High pressure pump;
- Membrane assembly; and
- Post treatment to stabilize the water, remove gases and adjust pH.

Forward osmosis employs a passive membrane filter that is hydrophilic, slowly transmits water, and blocks a portion of solutes. Water is driven across the membrane by osmotic pressure created by the lesser concentration on the clean side of the membrane. Low energy inputs are required, however such configurations have a relatively low output capacity. This method is often used for emergency purposes, such as in floodwater conditions.

5.2.2.3 Membrane Filtration Methods

Membrane filtration technology comes in different forms for different uses and extent of water desalination/purification required. The membranes are typically made of organic polymers and pore configurations include hollow fibre, spiral wound, cartridge and tubular. The three main methods, from "loosest" to "tightest" level of filtration are as follows:

- Microfiltration which is capable of removing particles of sizes down to 0.1 microns, including fine sediment, bacteria, algae, and some other bacteriological constituents.
- Ultrafiltration can remove particles as small as 0.005 microns, and can remove larger organic molecules and viruses.

- Nanofiltration, unlike the other two types, requires pressurization of the feed water. It can remove smaller particles than ultrafiltration (down to 0.0005 microns) and is able to remove organic molecules and discoloration, hardness (calcium and magnesium ions), and radionuclides.

Because it is the only one that actually removes dissolved ions, nanofiltration is often considered to be the only real desalination process of the three. All three allow passage of most metal ions and salts. Membrane filtration, therefore, is most commonly used in combination with an RO or EDR process as a method of pretreatment, but nanofiltration can be used as a stand-alone process for hard water that is otherwise acceptable for use (pers. comm. Yust, 2007).

5.2.3 *Other Technologies*

5.2.3.1 Freezing

During the freezing process, dissolved salts are naturally excluded during the initial formation of ice crystals. Before an entire mass of water has been frozen, the mixture is washed to remove salts adhering to the ice crystals. The ice is then melted to produce fresh water which is collected as product. This process can be used to desalinate seawater (Buros, 2000). A few freezing plants have been built over the last 50 years, however, it has not been a commercial success (Buros, 2000).

5.2.3.2 Hybrid Facilities

A method of reducing overall costs of desalination can be the use of hybrid systems using both RO and distillation processes. Such a system could provide a more suitable match between power and water development needs (Buros, 2000).

5.3 Concentrate Management

There are five conventional concentrate disposal methods. These are:

- surface water disposal;
- sewage disposal;
- deep well injection;
- evaporation ponds; and
- land application.

Other methods include Zero Liquid Discharge (ZLD) systems which reduce concentrate to a solid product for landfill disposal. Also, reuse/recycling by blending of concentrate with dilute power plant cooling water or treated wastewater effluent is used in some areas. Following, is a description of the various methods.

5.3.1 *Surface Water Disposal*

Surface water disposal is often associated with direct discharge to the ocean for seawater desalination, however it is in common use in inland areas as well. About half of the desalination plants in the United States use surface water disposal of concentrate to canals, rivers or lakes (pers. comm. Mickley, 2007). It is the cheapest and simplest method, since all that is needed is a pipeline and outfall structure. Its use may be restricted however, by local regulations, due to salt loading risks in fresh surface water bodies.

5.3.2 *Sewage Disposal*

Sewage disposal is used for about 25% of desalination plants in the U.S. (pers. comm. Mickley, 2007) and is also not only applied to seawater desalination. As with Surface Water Disposal, this can be subject to regulations and permitting in many areas. The capacity of wastewater treatment plants to handle the concentrate is also a consideration.

5.3.3 *Deep Well Injection*

Deep well injection involves pumping of concentrate waters into wells screened in deep, isolated aquifers by pumping through a feeder tube into the deep well, which contains a packer system for isolating the target aquifer. The use of deep well injection is limited by regulations as well as the availability of deep aquifers that are suitable for accepting concentrate waters. In the United States, deep well injection is mostly practiced in the State of Florida, with some also in Texas and California (pers. comm. Mickley, 2007) where suitable high-permeability aquifers are present. In many jurisdictions, however, such as Nevada, deep well injection is illegal, and in many areas, permeable, structurally isolated aquifers are not present.

5.3.4 *Evaporation Ponds*

Retention of concentrate water in shallow man-made ponds is quite common, however, the practice is limited to relatively small desalination facilities located in arid areas. As water is evaporated from the ponds, salts are left behind. Use of sprayers and blowers has been tested as a means of enhancing evaporation rates. Barriers and screens are often needed to prevent drifting of salt. Evaporation ponds are most cost effective in arid areas such as the southwest U.S. and the Middle East.

5.3.5 *Land Application*

Use of concentrate for land application methods such as irrigation is used only where groundwater standards allow, relatively small volumes of concentrate are produced, and plenty of land is available for a wide distribution (pers. comm. Mickley, 2007).

5.3.6 *Zero Liquid Discharge*

Zero liquid discharge (ZLD) concentrate management facilities use systems such as thermal evaporators, crystallizers, and spray dryers to reduce concentrate to a solid product for landfill

disposal. This can be practiced where regulations allow, and relatively small amounts of concentrate are produced. It is very energy intensive, however this limitation can be reduced by introducing highly concentrated discharge from RO desalination, or producing highly concentrated brine using ZLD, which, in turn can be introduced to an evaporation pond.

5.3.7 *Reuse/Recycling*

Blending of concentrate with wastewater treatment effluent or power plant cooling water is practiced in some areas. Such practice may be more acceptable to regulatory bodies than many of the other concentrate management options however, that is dependent on the ultimate fate of the blended stream.

At smaller scales, use of concentrate for dust suppression, roadbed stabilization, soil remediation, or other local activities may be considered in some areas.

5.4 *Cost-Benefit Analysis*

5.4.1 *Cost Factors*

There are numerous factors that affect costs of desalination and concentrate management technologies. These include:

- The amount of salt to be removed from a given amount of water. The more salts to be removed, the more expensive the desalination process;
- The capacity of desalination plants. The larger plants are generally more economical due to economy of scale principles;
- Energy requirements are the most significant cost factors. Energy contributes about 20% to 50% of the operating cost, depending on technology used and fuel prices (American Membrane Technology Association, 2005);
- Concentrate Management typically ranges from 5% to 33% of produced water cost (Tsiourtis, 2001);
- Amount and type of pretreatment required;
- Regulatory Issues;
- Land Costs; and
- Water conveyance costs.

Cost factors and general practicality of the use of desalination /concentrate management technologies in a given area are also dependent on site-specific activities and conditions. The following sections attempt to summarize the various considerations for choosing an appropriate type of facility. Desalination and concentrate management will be considered separately.

5.4.2 *Desalination*

Table 8 summarizes the benefits and drawbacks of the various desalination technologies that have been discussed, and also provides a cost comparison where available data allows. Note that costs are given from a variety of sources, and represent estimated costs for a medium-sized plant (approximately 5000 m³ daily capacity). The costs obtained from older sources have been adjusted for rate of inflation to approximate 2006 Canadian Dollars. These costs are presented for orientation purposes only and in many cases may not represent current actual costs.

Table 8 Cost-Benefit Considerations For Desalination Technologies

Desalination Technology	Benefits	Limitations	Salinity Range	Flow Range (m³ per day)	Locations of Application	Approximate Capital Costs (for average-sized plant) (millions of dollars)	Operating Costs (for average-sized plant) (millions of dollars)	Production Costs (for average-sized plant) (per m³)
Multi-stage Flash	Improvements in efficiency, better resistance against scaling, time-tested technology.	Energy intensive	Seawater	4,000 – 57,000 (Buros, 2000)	Middle East	\$3.6-5.8 per year (TTWP, 1998), \$7(UN, 1995)	\$1.8M (UN, 1995)	\$0.70-5.45 (Miller, 2003)
Multiple Effect	Improvements in efficiency, time-tested technology.	Energy Intensive	Seawater	2,000 – 20,000 (Buros, 2000)	India, the Caribbean, Canary Islands, United Arab Emirates	\$2.6-4per year (TTWP, 1998)	No data	\$0.27-1.51 (Miller, 2003)
Vapour Compression	Simplicity and reliability.	Less energy intensive than other distillation processes. Mechanical vapour compression has a limited flow range	Seawater	500-20,000 (Buros, 2000)	Middle East and others	No data	No data	\$0.46-\$1.23 (Miller, 2003),
Membrane Distillation	Simplicity, need for only small temperature differentials to operate	Large amounts of water must be used for low differentials – affects energy efficiency	Mainly seawater	No data	No data	No data	No data	No data
Solar Humidification	Simplicity, free thermal energy	Requires large collection area (0.25 square meters per liter per day), high water transfer costs, high maintenance	No data	4,000 is considered large (Buros, 2000).	Haiti, Mexico, United States	No data	No data	No data

Desalination Technology	Benefits	Limitations	Salinity Range	Flow Range (m³ per day)	Locations of Application	Approximate Capital Costs (for average-sized plant) (millions of dollars)	Operating Costs (for average-sized plant) (millions of dollars)	Production Costs (for average-sized plant) (per m³)
Electrodialysis	High recovery, can handle higher turbidity than RO.	Requires pretreatment, electrical energy required for electrodes, EDR prevents scaling/unwanted deposits	Brackish, most economical up to ~5000 mg/L	Average around 10,000, (UN, 2001)	Saskatchewan Texas, Middle East	\$0.6-0.9 per year (TTWP, 1998)	No data	\$0.58 (Miller, 2003), \$0.04 (pers. comm. Kalaswad, 2007)
Reverse Osmosis	Most common system for brackish water	High pressure feed required, requires membrane pretreatment if salinity is variable	5,000 – 45,000 mg/L	1000 – 50,000 (Metito, 2006)	Canada, Texas, Florida, Middle East	\$0.6-1.2 per year (TTWP, 1998), \$1.7-\$2 per year (Henthorne, 2005), \$2.1-2.6 per year (TWDB, 2006)	\$0.25 per year (TTWP, 1998), \$0.6-0.8 (Henthorne, 2005), \$1.3 (UN, 1995)	\$0.32-0.40 (Henthorne, 2005), \$0.46 (Metito, 2006)
Membrane Filtration	Simplicity, useful as pretreatment for RO	Does not remove all salts on its own	Moderately saline/hard water	Most often used with RO	Most often used with RO	~\$1 per year (Henthorne, 2005) \$1.8 per year (Parsons, 2005)	~\$0.1 per year (Henthorne, 2005)	\$0.04-\$0.05 (Henthorne, 2005), \$0.25 - \$0.27 (Parsons, 2005)
Freezing	Lower energy requirements than distillation, reduced scaling/precipitate problems.	Ice/water mixtures are mechanically complex to move and process	Any	No data	No data	No data	No data	No data

TTWP – Trans-Texas Water Program
UN – United Nations

Costs given in Table 8 are dependent on plant capacity, but costs are also affected by the quality of the feed water. Figure 1 shows the relationship between combined capital and operation costs and TDS concentration of feed water for a medium-sized (5000 m^3 daily capacity) RO plant, based on a cost-model formula from Metito Overseas Limited (2006). The relationship defines an exponential curve with the rise in cost increasing gradually with TDS input. There are subtle upward inflections in the curve around 10,000 and 30,000 mg/L TDS.

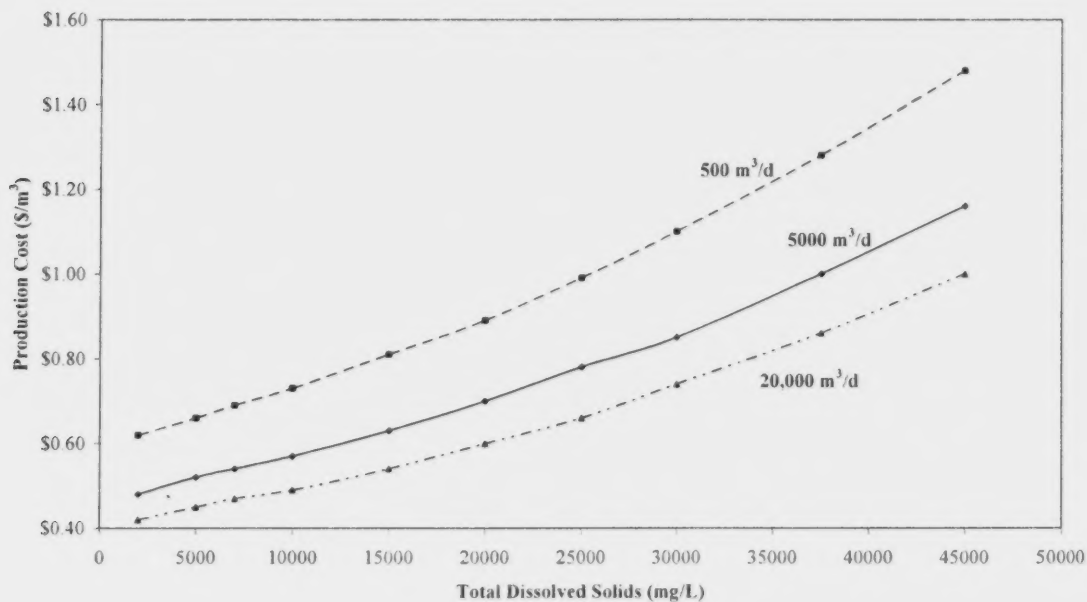


Figure 1 Production Cost vs. Feed Water TDS: Metito Cost Model for RO For Varied Plant Capacity

5.4.3 Concentrate Management

Table 9 presents a comparison of the various concentrate management options, in order of approximate relative cost for a medium-sized facility.

Table 9 Cost-Benefit Considerations For Concentrate Management

Concentrate Management Technology	Benefits	Limitations	Locations	Relative Capital Costs (Mickley, 2005)
Disposal to Sewer	Easy to implement if regulations allow. The cheapest of all methods.	Subject to the capacity/permission of the receiving water treatment facility.	Florida and other locations in the United States.	The lowest costing (requires pump, discharge line, and permits)
Disposal to Surface Water	Easiest and among the cheapest. Most common method used	Regulatory barriers in many areas, salt loading risks to surface water bodies	United States (mainly Eastern and Northern States)	One of the lowest costing, similar to sewer – includes pump, discharge line, and outfall structure.
Land Application	A sustainable solution where small amounts of concentrate are involved	Useful only in southern (United States) climates, effluent must meet groundwater standards	Florida and other southern areas (United States)	Similar level of cost to deep well injection (Intermediate level)
Deep Well Injection	Effective where permeable, low water quality aquifers are present	Limited to areas with suitable aquifers	Florida, Texas, California	Similar to land application. Cheaper for larger facilities
Zero Liquid Discharge	Solid product that can be disposed of in landfills	Energy intensive, regulatory barriers, and point source contaminant issues	California (pilot plant)	One of the most costly. Similar to Evaporation Ponds
Evaporation Ponds	System is relatively simple	Land costs are prohibitive for large facilities, mainly limited to hot, arid climates.	Florida, Texas, Arizona, Wyoming, Israel	Most costly
Reuse/Recycling	Enhances sustainability of concentrate management	Ultimate fate of concentrate is still an unsolved problem		Can be used to reduce costs and supplement water needs for some industries

5.5 Application in Alberta

Before evaluating cost-benefits for various desalination/concentrate management options, many options can be eliminated as being not viable in the Alberta setting in terms of regulatory barriers, high costs, climatic factors, and local challenges.

5.5.1 Desalination

Distillation methods are used primarily for seawater desalination due to the high energy requirements for this method. Application of these methods to brackish water is simply not cost-effective since a relatively small amount of salt is removed for the amount of energy consumed to drive the process.

Membrane methods such as EDR and RO, are more suitable for brackish water desalination. EDR is used in some communities in Saskatchewan (pers. comm. Shaheen, 2007) and both RO and EDR are being used in Texas (TWDB, 2006). RO is the most common method of brackish water desalination and is currently being used in rural households in Alberta.

Variability in feed water quality, or fairly hard water may necessitate some form of pretreatment such as membrane filtration. The cost of the use of the membrane pretreatment is offset by the enhanced recovery of product water. An illustrative example of this is in Tampa, Florida where a large desalination plant experienced fouling of its RO system, and could not achieve peak water production. This was due to the inadequacy of its original porous media-based pretreatment system. It has been suggested that an ultrafiltration membrane pretreatment in combination with RO is generally the most efficient and cost-effective configuration in many areas, including Alberta (pers. comm. Yust, 2007). Treatment of secondary effluent from the Goldbar Wastewater Treatment Plant in Edmonton is one example of treatment in Alberta using this configuration. The treated effluent at Goldbar is, in turn, used by Petro Canada's Edmonton Refinery.

In summary, the following desalination technologies were determined to be appropriate for most applications in Alberta:

- Reverse Osmosis;
- Electrodialysis Reversal; and
- Membrane Pretreatment (ultrafiltration is considered most cost-effective).

5.5.2 Concentrate Management

An even bigger concern in inland areas such as Alberta is the fate of desalination reject brine or concentrate, since seawater disposal options are not available. Current regulations would likely block any attempts to practice disposal to surface water or land application to any extent. Application to surface water is a common practice in the northeast United States, where surface water is in more abundance. Low TDS CBM product water is disposed of in ephemeral streams in Wyoming, but brackish water is produced from formations in the south and west of the state, so evaporation ponds and deep well injection are more suitable options (pers. comm. Frederick, 2007).

Deep well injection has already proven to be a challenge as applied to the oil and gas industry in Alberta, however some suitable aquifers do exist, so it may be a viable option in some areas. Use of conventional evaporation ponds on a large scale is not likely since the climatic conditions in Alberta, despite being semi-arid, are not conducive to the extremely high evaporation rates required for this method to be effective. However, evaporation ponds could be viable for use in the CBM developments, as in Wyoming, due to the relatively small amounts of product water. It could also be applied in a limited way to oil and gas or other large industries, which would be more able to absorb the high costs of land area needs and limited efficiency (pers. comm. Mickley, 2007).

Reuse/recycling is an attractive option, but the ultimate fate of the concentrate or concentrate blend must eventually be considered. Zero liquid discharge is the ultimate goal in concentrate

removal, however it is probably the most expensive method due to high energy requirements of reducing concentrate to a solid product. The capacity, or lack thereof, for landfills to accept the large quantities of product salts could also be prohibitive. Mike Mickley (pers. comm., 2007) suggested that a ZLD process would likely be the best option for Alberta desalination projects in areas where deep well injection is not viable. Mickley (2005) also suggests that costs can be offset by maximizing desalination system recovery prior to the ZLD process.

To summarize, the following configurations are deemed most applicable for potential concentrate management practices in Alberta:

- Zero Liquid Discharge (ZLD);
- Deep Well Injection (where suitable aquifers exist); and
- Evaporation Ponds (for small scale operations and industries for which costs are a limited issue).

5.5.3 Feasibility Summary

As described above, desalination options are few, and concentrate management is a challenge, however, these options are currently in use in several areas in North America and around the world, as this review has shown. Currently, water is cheap to use in Alberta (approximately \$0.10 per m³ for rural supplies), and treated brackish water from a desalination facility would be expected to carry a significantly higher cost. As shown in Table 8, the production costs are generally on the order of 3 to 5 times higher than this, however these are still mostly well below Enviroline's (2007) projection of \$1.50 per m³ as the true current value of water. Even more significant is the difference in capital costs between desalination options and current rural systems, however, these are mostly one-time costs. Operation and maintenance costs are high also, but at the same time, opportunities are also available to offset these costs. Use, reuse and recycling of concentrate are among the possibilities. Current research initiatives are not only directed toward improving the available technologies, but also to bring costs down. Since the 1970's, brackish water desalination costs have decreased by approximately a factor of 3 (American Membrane Technology Association, 2005).

5.6 Other Considerations

5.6.1 Transportation costs

The cost factor which is common across all forms of desalting facility is that of water transportation (Younos, 2005). This includes costs of conveyance of source water to the treatment facility (however, the facility is typically located close to the water source), as well as conveyance of product water or concentrate water to the desired user or receptor. Transport of water can be achieved using pipelines, tunnels or canals, from fixed, relatively permanent sources and receptors, but transport by truck is often required for isolated or short-term sources such as CBM wells. For pipelines, a series of pump stations is often required to keep water moving over long distances, since water has to be moved up-hill across areas of variable topography.

Little has been published in the scientific literature on the costs of transporting water, and comparisons between sources can be difficult. Henthorne (2005) indicates that transportation (including intake, outfall, storage and pumping) typically accounts for roughly 20-25% of capital costs. This can vary, however, depending on transportation distance and available infrastructure.

Zhou and Tol (2004) discuss numerous examples of water transport worldwide, the costs of which range from approximately 5 to 20 cents per m^3 per 100 km horizontal distance for various examples including pipelines and canals. Note that it is vertical movement of water, not horizontal distance that is the main driver of water transport cost. Vertical distance however, is variable among the example sites, so the costs are given as per unit horizontal distance for the purposes of a general comparison

Where such conveyance systems are not feasible, options such as the use of tanker trucks may have to be considered. The United States Department of Energy (2002) estimates a typical water trucking cost of approximately \$13 per m^3 , while anecdotal information suggests that truck transport can add up to \$40/ m^3 to water disposal costs.

The advantages of using RO and EDR plants for the supply of potable water for smaller communities include the low initial capital costs due to its compact, multi-configuration design, short construction time, low energy requirements and the flexibility to upgrade from small to large-scale units with increasing demand. These units are generally located close to water sources and within the communities to reduce many of the costs associated with transportation.

5.6.2 *New Research Directions*

The high costs and limitations of the various desalination and concentrate management technologies necessitate research in reducing energy and concentrate disposal costs, reducing costs of desalination processes, finding beneficial uses of reject waters, minimizing impacts of concentrate disposal, preventing biofouling, recycling and reuse strategies, and new membrane designs.

The following lists some of the latest research initiatives in desalination:

- Capacitive deionization technology uses carbon electrodes and the potential between negative and positive charges to selectively remove ions (pers. comm. Kalaswad, 2007).
- Self-sealing evaporation ponds for concentrate disposal. It involves adding chemicals to concentrate brine so that it forms its own evaporation pond liner (pers. comm. Kalaswad, 2007).
- Selective removal of salts from ZLD concentrate (Mickley, 2005). A method of removing individual salts from concentrate has been developed by Geo-processors Ltd. of Australia. The separated salts can be produced for sale and applied to various practical uses.
- Vibratory shear enhanced processing is a process by which stacks of membranes are vibrated very fast to generate shear forces. This pushes solids away from the membrane to prevent build-up of deposits and enhance recovery.

5.6.3 *Cogeneration and Alternative Energy Sources*

Cogeneration is the use of a single energy source for several different functions. Distillation plants in particular, are often built to produce both desalted water and electricity. Most commonly, steam produced in the distillation process, can, in turn, be used in turbines. The obvious advantage is that the electricity produced can go back into the desalination process, thereby reducing the consumption of fuel and energy costs.

Some desalting units that use solar or wind energy to operate have been built to work with standard processes such as RO, electrodialysis and distillation. Costs are generally higher than with conventional power generation, but as the costs of the new technologies are reduced, and conventional fuel prices rise, solar and wind power for new desalination facilities may become more common. Moves toward more strict environmental regulations in future may also provide added incentive for exploring these and other alternative power sources. The International Desalination Association's inventory from 1998 lists about 100 known wind or solar powered desalination plants scattered among 25 countries. Most of these however, have capacities of less than 20 m³ per day (Buros, 2000).

6.0 CONCLUSIONS

Most provinces in Canada do not distinguish between saline and brackish water in their regulations, whereas most states do. The various states studied have different approaches to doing so, for example Montana uses specific conductance to distinguish saline groundwater and Texas follows the United States Environmental Protection Agency using TDS.

Applicable desalination technologies for Alberta are essentially limited to reverse osmosis and electrodialysis, based on costs, suitability for the quality of the potential source water (brackish), and the established use of these same methods in other areas such as Saskatchewan and Texas. Desalination technologies are most cost-effective for potable water supplies, compared to agricultural use. In terms of concentrate management in Alberta, zero liquid discharge is likely the most cost-effective in terms of land costs as a second to injection wells which are not always an option. Costs of desalinated brackish water would likely be 3 to 5 times higher than the current costs of usable water in Alberta.

It is clear from the cost-benefit analysis that marginally saline groundwater has the potential to represent a valuable future source of water. The management and protection of this resource is consistent with the Water for Life Strategy, particularly in meeting the objectives of a Healthy Aquatic Ecosystem, by providing alternatives to the use of fresh water resources, and in providing Reliable, Quality Water Supplies for A Sustainable Economy by presenting additional resources to meet that objective. Industrial use of this resource, in particular for oilfield injection, is already encouraged and being utilized. In areas where surface water allocations are no longer permitted and non-saline groundwater sources may be limited, marginally saline groundwater is expected to represent a vital resource to sustaining economic growth.

Several areas of further investigation regarding the use of saline groundwater in Alberta are as follows:

1. Additional information should be collected in order to establish the availability of marginally saline groundwater and identify areas where this could represent a potential resource, particularly for drinking water supplies. These knowledge and research efforts include:
 - 1.1 Complete a water balance to establish the magnitude of brackish groundwater in Alberta. When doing a study of the quantity and quality of brackish water available, some other aspects to keep in mind are: population densities, agriculture distribution, hydrogeology, geology, soil suitability, water well distribution and the origin of the brackish water.
 - 1.2 Mapping efforts currently underway by the Alberta Geological Survey will be valuable in establishing the overall resources.
 - 1.3 Review existing information on brackish groundwater use, to establish amounts and locations of current use. Collaboration with the EUB will be valuable in collecting information regarding produced saline groundwater. This would provide a

preliminary understanding of the locations of marginally saline groundwater aquifers in Alberta.

- 1.4 Prioritize locations of potential brackish groundwater availability and potential use to focus on water short areas for a mapping program to determine the locations and extent brackish groundwater aquifers and available resources
2. With respect to application by specific user groups the following recommendations are provided relating to knowledge and research and intended to target areas identified with potential marginally saline groundwater aquifers in fully allocated basins or take advantage of marginally saline groundwater production from CBM wells:
 - 2.1 Identify communities suitable for pilot programs for treatment of marginally saline groundwater.
 - 2.2 As part of these pilot studies, conduct research into the application and optimization of the viable desalination/concentrate management technologies indicated in this report.
 - 2.3 Conduct additional research into alternative desalination technologies that may be feasible in areas of unique local challenges (i.e., scale, groundwater conditions, aquifer depths and characteristics).
 - 2.4 Establish pilot studies to investigate the viability of direct application and/or water blending for agricultural users. These studies may be appropriately initiated by the Prairie Farm Rehabilitation Association or Alberta Agriculture, Food and Rural Development.

7.0 LITERATURE CITED

- Agriculture and Agri-Food Canada (2005) Emergency Water Supply Options During Drought. Available at: <http://www.agr.gc.ca/pfra/drought/info/EmerWaterSup_e.htm> Accessed 2007 January 25.
- Alberta Agriculture, Food and Rural Development (2005) Irrigation Districts Annual Water rates. Irrigation Branch, Lethbridge. Last reviewed August 2006. Available at: <[http://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/irr8780](http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr8780)> Accessed 2007 February 13
- Alberta Agriculture, Food and Rural Development (2003 May 1) Pasture Water Systems for Livestock. Available at: <[http://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/agdex644?open=document](http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex644?open=document)> Accessed 2007 January 1
- Alberta Environment (AENV) (2005 August) Focus on Groundwater. Available at: <http://www3.gov.ab.ca/env/water/GWSW/quantity/learn/what/GW_GroundWater/GW1_introduction.html> Accessed 2007 February 28.
- Alberta Environment (AENV) (2002a) Water for Life: Facts and Information on Water in Alberta 2002. Government of Alberta.
- Alberta Environment (AENV) (2002b May) Water for Life: Results from completed workbooks: copy of workbook. Sub-report No. 1, section a.
- Al-Hadidi MS (1999) Brackish Water Management and Use in Jordan. Desalination 126 (1999) 41-44.
- American Membrane Technology Association (2005) Membrane Technology Facts. Stuart, Florida. Available at: <http://www.membranes-amta.org/publications_facts.html> Accessed 2007 February 28.
- Bachman S, Hauge C, McGlothlin R, Neese K, Parker T, Scracino A, Slater S (2005) California Groundwater Management, second edition. Groundwater Resources Associated of California. Chapter 1, pg 16.
- Berardinucci J, Ronneseth K (2002 June) Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater. Ministry of Water, Land and Air Protection.
- British Columbia Ministry of Environment (2005 July 1) Environment Management Branch. Code of Practice for the Discharge of Produced Water from Coalbed Gas Operations B.C. Reg 156/2005.

- Buros OK (2000) The ABCs of Desalting, 2nd Ed. International Desalination Association, Topsfield, Mass.
- Canadian Council of Ministers for the Environment. 1999. Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses. In: Canadian Environmental Quality Guidelines, 1999. Canadian Council of Ministers for the Environment, Winnipeg.
- CBS News (2006 October) Should Albertan pay more for their water? Available at: <http://www.cbc.ca/news/story/2006/10/27/water-alberta.html>.> Accessed 2007 January 18.
- Chinese Government (2002) Water Law of the People's Republic of China. Order of the President No. 74.
- Department of Environment and Natural Resources Division of Water Quality (2005 December) North Carolina Administrative Code (NCAC) Title 15A. Subchapter 2L. Classifications and Water Quality Standards Applicable to the Groundwaters of North Carolina. Section 0300: Classifications and Groundwater Quality Standards.
- The Department of Environmental Quality in Wyoming (DEQ) (2005 March) Quality Standards for Wyoming Groundwater, Chapter 8 and Chapter 13. Water Quality Rules and Regulations.
- The Department of Environmental Quality in Wyoming (DEQ) (2004 September) Underground Injection Control. Available at: <http://deq.state.wy.us/wqd/groundwater/uicprogram/index.asp>.> Accessed 2007 February 28.
- Energy and Utilities Board (EUB) (1994 March) Directive 051: Injection and Disposal Wells: Well Classification, Completion, Logging and Testing Requirements. Last updated February 1, 2006.
- Enviroline (2007) Enviroline Online. Vol 17: No 3 and 4, pgs 19-21.
- Environment Canada (2006 October) Water – How we use it. Available at http://www.ec.gc.ca/water/en/info/pubs/primer/e_prim03.htm.> Accessed 18 January 2006.
- Fetter CW (1994) Applied Hydrogeology. Third Edition. Prentice-Hall Inc. Pg 434.
- Florida Department of Environmental Protection (DEP) (2007) Underground Injection Control Program. Last updated January 19, 2007. Available at: <http://www.dep.state.fl.us/water/uic/index.htm>.> Accessed February 28, 2007.
- Florida Department of Environmental Protection (DEP) (2004 July) Integrated Water Quality Assessment for Florida: 2004 305 (b) Report and 303(d) List Update.
- Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ, pg 84.

- Government of Alberta (2006) Water Conservation and Allocation Policy for Oilfield Injection. Water for Life.
- Government of Manitoba (unknown date) Water Stewardship. Manitoba Water Quality Handbook. A Valuable Resource. Available at:
<http://www.gov.mb.ca/waterstewardship/water_guide/resource/groundwt.html>
Accessed 2007 February 15.
- Ground Water Protection Council (1999 October). Ground Water Report to Congress. Summaries of State Ground Water Conditions.
- Groundwater Services Inc., Houston, Texas. (2003 November) GSI Regulatory Update Bulletin. TRRP-8: Groundwater Resource Classification.
- Health Canada (2006 March) Guidelines for Canadian Drinking Water Quality. Summary Table. Prepared by the Federal-Provincial-Territorial Committee on Drinking Water of the Federal-Provincial-Territorial Committee on Health and the Environment.
- Hem JD (1970) Study and Interpretation of the Chemical Characteristics of Natural Water, U.S. Geological Survey Water-Supply Paper 1473.
- Henthorne L (2005) Economic Evaluation of Membrane and Conventional SWRO Pretreatment – Results from a Pilot Study. American Waterworks Association, Membrane Technology Conference.
- The International Development Research Centre (IDRC). Government of Canada. More on water in Jordan... Available at: <http://www.idrc.ca/en/ev-65877-201-1-DO_TOPIC.html>
Accessed 2007 February 12.
- Karajeh F, BenJemaa F (2004) A Legislative Boost for Water Desalination as an Alternative Water Supply Strategy in California. Water Conservation News – Fall/Winter 2004/05.
- Kenzie OR (unknown date) Looking Back on Water Societies in Southern Alberta. Available at:
<http://www.quantumlynx.com/water/back/vol2no1/v21_st3.html> Accessed 2007 January 18.
- Metito Overseas Ltd. (Metito) (2006) Desalination Water Cost Modeling Variables. Available at:
<<http://www.medrc.org.om/>> Accessed 2007 February 28.
- Mickley M (2005) Review of Concentrate Management Options. State of Science Report. Available at: <<http://www.twdb.state.tx.us/Desalination/Desal/Volume2Main.asp>>
Accessed 2007 February 28.

- Mickley M (2001 September). Membrane concentrate Disposal: Practices and Regulation. Final Report. Desalination and Water Purification Research and Development Program Report No. 69.
- Miller JE (2003) Review of Water Resources and Desalination Technologies. Sandia National Laboratories, Albuquerque, NM. Available at: 49pp. <<http://www.wraconsultants.com/romodel.htm>> Accessed 2007 February 28.
- Ministry of Environment of Ontario (2005b April) Permit to Take Water (PTTW) Manual.
- Ministry of Environment of Ontario (2005a October) Green Facts. Permit to Take Water.
- Mukherji A, Shah T (2005) Groundwater Socio-ecology and Governance: A Review of Institutions and Policies in Selected Countries. *Hydrogeology Journal* (2005) 13:328-345.
- Multi-advisory committee (2004) Alberta Environment Guidelines for Groundwater Diversion For Coalbed Methane/Natural Gas in Coal Development.
- Multi-stakeholder Advisory Committee (2006) Coalbed Methane/Natural Gas in Coal. Final Report.
- Parsons International and Company, LLC (Parsons) (2005) Brackish Water Development Study. Prepared for the Water Resources Development Dept., Ministry of Regional Municipalities, Environment and Water Resources, Sultanate of Oman, January 2005.
- Prairie Farm Rehabilitation Administration. Available at: <http://www.agr.gc.ca/pfra/water/livestck_e.htm>. Accessed 2007 January 24.
- Pretula B (1984) Base of Groundwater Protection – Useable Water. Modified summary provided by Alberta Environment.
- Province of Alberta (1998) *Water Ministerial Regulation*. Alta. Reg 205-98.
- Province of Alberta (1996) *Water Act*. Statutes of Alberta, Chapter W-3.5 with amendments.
- Province of British Colombia (2006 September 21) Environment Management Act Hazardous Waste Regulations. BE. Reg. 261/2006.
- Province of British Columbia (2002) *Environmental Assessment Act*. Chapter 43. Queen's Printer.
- Province of British Columbia (1996) *Water Act*. Chapter 483. Queen's Printer.
- Saskatchewan Industry and Resources (2003 April) Application for a Waste Water Disposal Well PNG Guideline 6.

- Saskatchewan Watershed Authority. Regional Groundwater Resources Assessments. Available at: <<http://swa.ca/WaterManagement/Groundwater.asp?type=Assessments>> Accessed 2007 February 15.
- Saskatchewan Watershed Authority (2005) Policy Statement. Industrial Water Use Charges.
- Shekhar S (2006) An Approximate Projection of Availability of the Fresh Groundwater Resources in the South West District of NCT Delhi, India: a Case Study. *Hydrogeology Journal* 14: 1330-1338.
- State of California (2003) Assembly Bill No. 314. Chapter 206. An Act to Amend Section 12947 of the Water Code, relating to water. Approved by Governor August 9, 2003. Filed with Secretary of State August 11, 2003.
- State of Montana (2006) Administrative Rules of Montana (ARM). Montana Ground Water Pollution Control System. Environmental Quality Chapter 30, Water Quality, Subchapter 10.
- Texas Groundwater Protection Committee (2003 February) AS-188. Texas Groundwater Protection Strategy.
- Thomsen R, VH Sondergaard, KI Sorsesen (2004) Hydrogeological mapping as a basis for establishing site-specific groundwater protection zones in Denmark. *Hydrogeology Journal* 12:550-562.
- Tsiourtis NX (2001) Desalination and the Environment. *Desalination* 141:223-236.
- Trans-Texas Water Program (TTWP) (1998 February) Desalination Report. Technical Memorandum. TTWP Southeast Area.
- TWDB (Texas Water Development Board) (2006) Desalination FAQs. Texas Water Development Board. Available at: <<http://www.twdb.state.tx.us/iwt/desal/faq.html>> Accessed 2007 February 28.
- United Nations (2001) Water Desalination Technologies in the ESCWA Member Countries. UN Economic and Social Commission for Western Asia.
- United Nations (1995) Sourcebook of Alternative Technologies for Freshwater Augmentation in Some Countries in Asia. UN Environment Program Newsletter and Technical Publications. Available at: <<http://www.unep.or.jp/ietc/publications/techpublications/TechPub-8e/index.asp#1>> Accessed 2007 February 28.
- United States Department of Energy (2002 November) Powder River Basin Coalbed Methane Development and Produced Water Management Study.

- United States Environmental Protection Agency (USEPA) (2006 December) Underground Injection Control (UIC) Program. Available at:
<<http://www.epa.gov/safewater/uic/classes.html>> Accessed 2007 February 15.
- United States Environmental Protection Agency (USEPA) (2002 January) Protecting Drinking Water through Underground Injection Control. Drinking Water Pocket Guide #2.
- United States Environmental Protection Agency (USEPA) (1986 December) Guidelines for Ground-Water Classification Under the EPA Ground-Water Protection Strategy.
- United States Environmental Protection Agency (USEPA) (1984) Ground-Water Protection Strategy.
- United States Environmental Protection Agency (USEPA) (May 1980) Statement of Basis and Purpose Underground Injection. Control Regulations. Office of Drinking Water Environmental Protection Agency. National UIC program Docket Control Number D 01079.
- United States Geological Survey (1995) Preliminary Estimates of Water Use in the United States. Open-File Report 97-645.
- World Health Organization (WHO) (2004) Guidelines for Drinking-Water Quality. Third Edition Volume 1 Recommendations. Geneva.
- Younos T (2005) The Economics of Desalination. Journal of Contemporary Water Research & Education. 132:39-45.
- Zhou Y and RSJ Tol (2004) Evaluating the costs of desalination and water transport, FNU-41, revised, Centre for Marine and Climate Research, Hamburg University, Hamburg.

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